# A STUDY OF THE ADHESIVE WEAR IN THE PRESENCE OF MAGNETIC FIELD

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By
A. RADHAKRISHNA

*to the*

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*With*

*love and affection*

*I*

*dedicate*

*to*

*my parents*

# CERTIFICATE

Certified that this work entitled "A Study of the Adhesive Wear in the Presence of Magnetic Field" has been done by Shri A. Radhakrishna under my supervision and has not been submitted elsewhere for the award of a degree.

Mohan Krishan Muju
Department of Mechanical Engineering
Indian Institute of Technology
Kanpur

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# ABSTRACT

Wear of materials like brass, stainless steel and mild steel is studied in presence and absence of magnetic field. The experimental results are in agreement with the observations of the previous workers. It is postulated that the activation energy of wear would be reduced by the application of magnetic field. The effect of the feed on the gain factor was investigated. It was realised that the influence of magnetic field is primarily through its influence on adhesive wear. The postulates of the previous workers, that the magnetic field enhances the diffusivity seems to be consistant with the results obtained in the present work. The wear particles obtained at high speed are analysed in a proton induced X-ray emission analyser.

# CHAPTER I

# INTRODUCTION

## 1.1 Introduction

" ... a ring is worn thin next to the finger with continual rubbing. Dripping water hollows a stone, a curved plough share, iron though it is, dwindles inperceptibly in the furrow. We see the cobble stones of the highway worn by the feet of many wayfarers. The bronze statue by the city gates show their right hands worn thin by the touch of all travellers who have greeted them in passing. We see that all these are being diminished since they are worn away. But to perceive what particle drop off at any particular time is a powder grudged to us by our ungenerous sense of sight".

Lucretius (2000 years ago) [1]

Today with our most modern equipment we are for the first time beginning to be able to characterise "The particles that drop off at any particular time". Yet it still remains almost impossible for us to forecast the wear behaviour of any given sliding system.

The difficulty with wear studies is that in most particular situations the conditions at and below the sliding interface are very complex and there is naturally a

tendency to isolate each mechanism and perhaps over emphasize its role in the over all wear process. In the recent times, the wear researchers have been actively using techniques like

1) Electron microscopy (scanning & transmission)
2) X-ray diffraction
3) Auger emission spectroscopy
4) Chemical ething, etc.

for understanding the actual mechanism of wear.

The scientific research committee of the organization for economic cooperation and development has defined "wear as the progressive loss of substance from the operating surface of a body occuring as a result of relative motion of the surface" [2] . This is a very broad definition and according to this wear cover so many materials, sliding systems, operational conditions and types of measurement. It would be impossible for any single individual to understand the whole process. Wear is a complex process involving interaction between various fields of science and engineering. An individual can at best design an experiment which renders itself soluble to the extent to which a particular aspect is predominant.

## 1.2 Types of Wear

It is interesting to observe that inspite of the fact that enormous literature on wear is available, it has not been possible to enunciate a set of laws of wear. This is basically due to the nature of the phenomenon itself. The wearing behaviour of a pair of interacting solids would in general be governed by numerous factors like

1) Material homogeneity
2) Material properties
   a) resistance to fatigue loading,
   b) resistance to impact and shear loading.
   c) resistance to thermal effects like diffusion, etc.
3) Surface properties
   a) surface energy
   b) surface film behaviour
   c) surface residual stresses.
4) Presence of electrical and magnetic fields and others.

Some generalisation can however be made. The most commonly observed wear behaviour is that dry wear will increase with increase in load and velocity. The wear rate is higher for a softer material and a lubricant reduces the wear rate. Depending upon the materials and the magnitude of parameters involved, wear has been classified in three main groups as

i) Abrasion wear

ii) Adhesion wear

iii) Diffusion wear

i) Abrasion wear

This is the form of wear which occurs when a rough hard surface, or a soft surface containing hard particles, slides on a softer surface, and ploughs a series of grooves in it. The material from the grooves is displaced in the form of wear particles, generally loose ones.

ii) Adhesion wear

This is the form of wear which occurs when two smooth bodies are slid over each other and fragments are pulled off one surface to adhere to the other. Later the fragments may come off the surface on which they are formed and be transferred back to the original surface, or else form loose wear particles.

iii) Diffusion wear

Solid state diffusion is the mechanism by which atoms diffuse from one lattice point to another thus leading to a net transfer of matter from one body to the other one in the direction of the concentration gradient. This is possible, however, only when temperature conditions are favourable for atomic movement. Thus, if in the adhesion process localized temperature increases to a considerable

level interfacial diffusion can occur.

Diffusion wear has been seen to be of particular significance in the high speed machining process.

Wear has also been observed to occur due to fatigue conditions, fretting, corrosive conditions, etc. Several workers have studied the metal transfer between sliding bodies and it is well established that even at low speeds and loads the metal transfer does occur [3]. In present work also the attention is more confined to the study of adhesion wear across a sliding interface.

## 1.3 Review of Previous Work

Metallic wear in the presence of magnetic field seems to have been studied by a very limited number of researchers [4 - 9]. Ghosh and Bagchi [4, 5] reported the effect of magnetic field on the wear of cutting tools. They by means of repeating experiments established that magnetisation of H.S.S. tool cutting or rubbing against a mild steel job considerably reduced the wear rate of the tool. Increase in coherence of improvement in bonding affinity was thought as a possible reason. They defined gain factor $G_o$ as

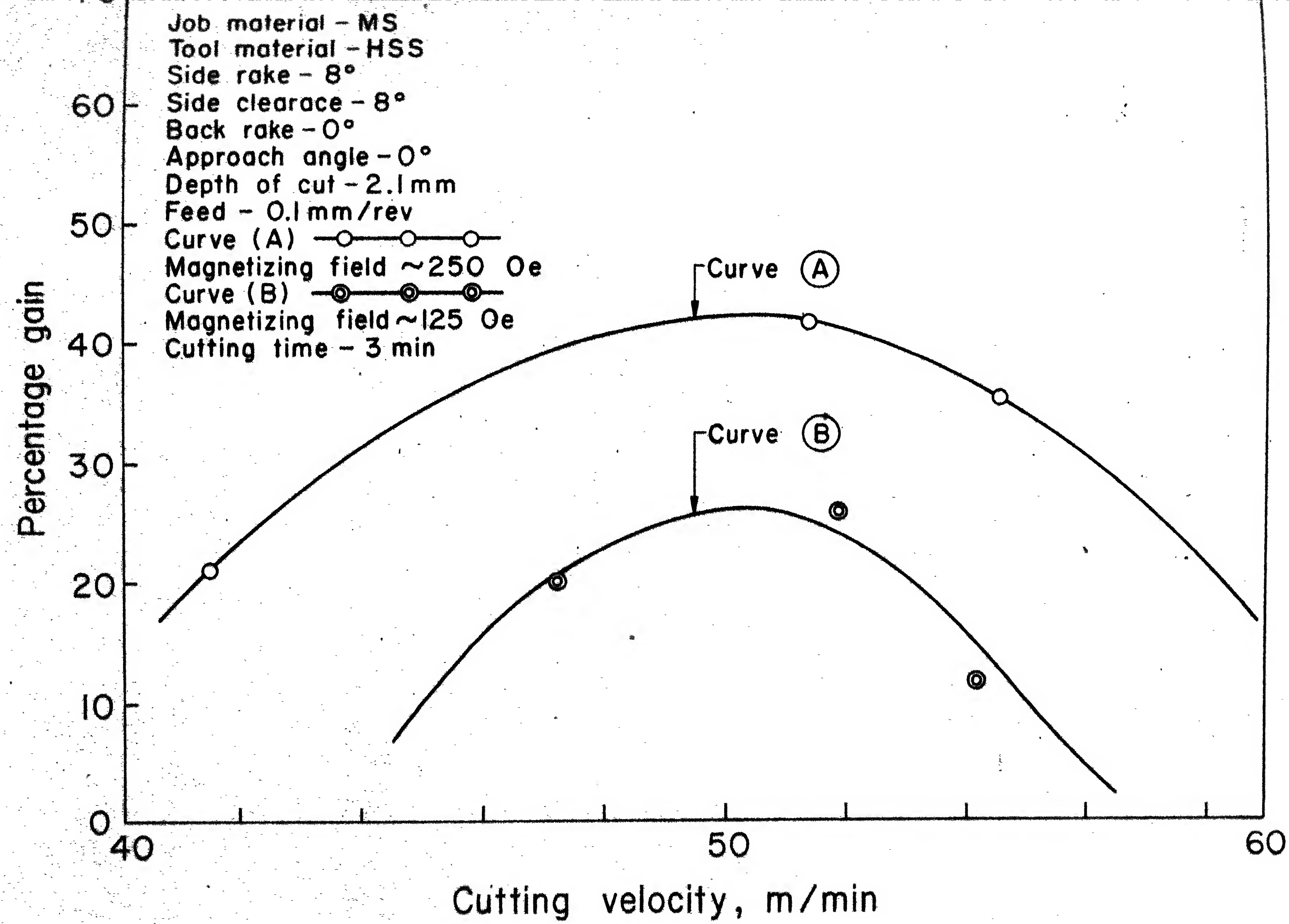
$$G_o = \frac{h_o - h_m}{h_o} \qquad (1.1)$$

where, $h_o$ and $h_m$ are the flank wears of the H.S.S tool in the absence and presence of magnetic field.

They found that the gain factor, $G_o$, is always positive for the H.S.S and mild steel combination, Fig. 1.

Similar increase in tool life has been reported [10, 11] while drilling and turning. All these tests have been basically done in presence of weak magnetic fields. Galie [12] has reported the increase in tool life by the application of a very strong magnetic field.

Muju and Ghosh [6, 9] have carried out fairly extensive investigations and their theoretical reasoning seems to be consistant with the experimental results obtained by several others. They have concluded that the magnetic field, basically, influences the adhesive wear behaviour of the rubbing pair. And the relative magnetic permeability seems to be the predominant factor. The effect of magnetic field is seen through its influence on the mobility of dislocations. They also suggest that the dislocation mobility should influence the diffusivity across the interface which can lead to different surface hardness gradient at the surface. The adhesive wear behaviour of the sliding pair can correspondingly get changed. It therefore appears that the application of the magnetic field basically alters the wear behaviour of the rubbing pair rather than the wear resistance of an individual body. And it may not be always advantageous to apply the magnetic field. In fact the surface deterioration in steel ball bearings, in electrical machines observed by



Job material - MS
Tool material - HSS
Side rake - 8°
Side clearace - 8°
Back rake - 0°
Approach angle - 0°
Depth of cut - 2.1 mm
Feed - 0.1 mm/rev
Curve (A)
Magnetizing field ~250 Oe
Curve (B)
Magnetizing field ~125 Oe
Cutting time - 3 min
Curve (A)
Curve (B)
Percentage gain
Cutting velocity, m/min
0
10
20
30
40
50
60
40
50
60

Simpson and Russel [13] , where large magnetic flux is present, could very well be due to the effect of magnetic field on wear.

Thus the adhesive wear phenomenon is basically considered to be a result of the interaction between the two bodies. They defined a mechanical interaction factor, $\lambda$ as

$$\lambda = n_I^o / n_{II}^o \tag{1.2}$$

where $n_I^o$ and $n_{II}^o$ are the number of asperities failing in body I and in body II respectively of a sliding pair. By proceeding in this manner they explained the wear behaviour of brass sliding against mild steel at various speeds in presence of magnetic field.

## 1.4 Objective and Scope of the Present Work

The results of Muju and Ghosh [8, 9] indicated that in situations where a non magnetic body is rubbing against a steel surface it may be desirable to apply an external magnetic field to reduce the wear of the non magnetic body.

There are several situations in electrical industry, textile and chemical industries where nonferrous materials like copper based, manganese based, or chromium based (stainless steels) alloys, are acting as sliders over steel shafts. It would be of interest to investigate as to

how the magnetic field would affect the wear behaviour of these bodies.

It is the objective of the present work to specifically study the wear of non-magnetic material rubbing against mild steel surface and find the primary causes for the changing behaviour of the wearing pair. Change in activation energy of diffusion due to the application of magnetic field is investigated and its influence on the gain factor is postulated. The mechanical interaction factor is investigated in light of the changing relative hardness at the asperities with the rubbing velocity.

It was contemplated to conduct a diffusion test in the deforming state of asperities in order to obtain the enhancement of diffusivity under strained condition. However limited time and facilities did not permit to undertake this test as a part of this work. Very useful experimental confirmation could be had through the extensive use of microprobe analysis or scanning electron microscopy. Due to the nonavailability of these facilities the objective of this work is mainly to observe the qualitative changes.

# CHAPTER II

## EFFECT OF MAGNETIC FIELD ON PLASTIC DEFORMATION AND WEAR

### 2.1 Introduction

The theoretical strength of a crystal free from defects is calculated to be $\approx \frac{G^*}{30}$, where $G^*$ is the shear modulus. However, experimental observations revealed that plastic deformation in actual crystals is initiated at stress $\approx 10^{-3} - 10^{-4}$ $G^*$. This is because of the fact that all real crystals contain defects, called dislocations. They are observed to move and increase in number when the crystals are subjected to deformation.

The movement of dislocations is along the slip planes of the crystal and are always mixed in character. Dislocations, found in real crystals, usually build-up characterstic networks depending upon the treatment to which the crystals have been submitted. Metal crystal prior to plastic deformation, after the heat treatment, have dislocation density of $\approx 10^7 - 10^8$ $cm^{-2}$. After considerable plastic deformation dislocation density increases to $10^{11} - 10^{12}$ $cm^{-2}$. [14]

Dislocation movement is basically either glide (conservative motion) or climb (non conservative motion).

One of the well accepted relationships for the dislocation velocity in gliding is [15]

$$V(\sigma, \theta) \propto \left(\frac{\sigma_a}{\sigma_o}\right)^n \tag{2.1}$$

where $V(\sigma, \theta)$ = velocity of dislocation for the applied stress and temperature,

$\sigma_a$ = applied shear stress resolved in the slip plane,

$\sigma_o$ = shear stress when V = 1 cm/sec.

n = a constant ($\simeq$ 25 for $Li_2F$ and $\simeq$35 for Fe - 3.25% Si).

It was observed that for dislocation motion by climb, is possible only when a large quantity of energy is available. However, this climb process takes place even when the available energy is small. So, in a plastic deformation the motion of dislocation climb process occurs by the formation of jogs. Jog is essentially a climb of a part of dislocation and not the climb of the whole dislocation. Jogs are formed only in an edge dislocation. The rate at which jogs climb depends upon the diffusion rate and stress assisting it. For large stresses the relationship for the dislocation velocity [16] is

$$V(\sigma, \theta) = V_o \exp \frac{V^* \sigma^*}{k\,\theta} \tag{2.2}$$

where $V_o = \frac{D\, C_J}{b}$ , $V^* \approx b_o^3$ and $\sigma^* = \sigma_a - \sigma_i$

$D$ = Diffusion coefficient,

$C_J$ = Concentration of jogs,

$b$ = Burgers vector,

$V*$ = Activation volume,

$b_o^3$ = Atomic volume,

$\sigma^*$ = Effective stress,

$\sigma_a$ = Applied stress,

$\sigma_i$ = Internal stress,

$k$ = Boltzman's constant,

$\theta$ = Operating temperature.

The rate of plastic deformation of a body depends directly on the dislocation velocity and is given by

$$\dot{\epsilon} = V(\sigma, \theta)\ \rho_m\, b \qquad (2.3)$$

where $\dot{\epsilon}$ = strain rate

$\rho_m$ = mobile dislocation density.

Combining equations 2.2 and 2.3 we have

$$\dot{\epsilon} = b\ \rho_m\, V_o \exp\left(\frac{V^*\ \sigma^*}{k\ \theta}\right) \qquad (2.4)$$

As can be seen from this equation, the dislocation velocity and hence the strain rate is sensitively dependent on effective stress and not just on applied stress. Temperature has no sensitive role as there is a

compensatory effect coming in due to the diffusion term. A simple calculation shows that the dislocation velocity at room temperature for iron would reach a value of order of $10^3 - 10^4$ cm per second.

## 2.2 Effect of Magnetic Field on Dislocation Velocity

When a magnetic field is applied to a deforming body the internal stress reduces due to magnetostrictive stress relaxation [17, 8]. Hayashi et al [17] have shown that in nickel the magnitude of fall in internal stress due to the application of magnetic field is of the order of 0.4 kg . $mm^{-2}$. The fall in the internal stress may cause considerable increase in the mobility of dislocations. Dislocations require extra energy to cross the domain walls. When a strong magnetic field is applied, most of the domain walls vanish and the mobility of the dislocation increases.

The relationship between the flow stress and internal stress for a crystalline material is given by [14]

$$\sigma_o = \sigma_i + K\, d^{-1/2} \tag{2.5}$$

where K = a constant

d = the grain size

$\sigma_o$ = flow stress

$\sigma_i$ = resistance to dislocation motion.

Stress relaxation experiments on mild steel [8] show that the application of a steady magnetic field ($H \approx 250$ Oe)

results in a decrease in internal stress as well as inflow stress. The reduction in the internal stress has been taken as the product of shear modulus $G^*$ and the magnetostrictive constant $\lambda_s$. Hence the increase in the effective stress due to the application of magnetic field is $G^* \lambda_s$. This works out to be about 50 kg . $cm^{-2}$ for nickle and iron. The effective stress in presence of magnetic field is therefore

$$\sigma^{**} = \sigma_a - ( \sigma_i - G^* \lambda_s)$$

$$= \sigma^* + G^* \lambda_s \tag{2.6}$$

Thus the effective stress at the same level of applied stress has been increased by $G^* \lambda_s$. Hence the velocity of dislocation with and without dislocation is given by

$$V^H = V_o \exp. \frac{V^* \sigma^{**}}{k \theta} \tag{2.7}$$

$$V^o = V_o \exp. \frac{V^* \sigma^*}{k \theta} \tag{2.8}$$

The influence of magnetic field on the dislocation velocity can be seen as

$$\frac{V^H}{V^o} = \exp. \frac{V^* G^* \lambda_s}{k \theta} \tag{2.9}$$

This ratio at 300 $^o$k for $\alpha$ - iron is approximately equal to 6.0. Therefore the plastic deformation rate should show an enhancement of 6.0 when a external strong magnetic field is applied. This was realised by Kamenetskaya et al. [18] in their creep tests also. Muju and Ghosh [6 - 8]

believe that the primary result of the application of magnetic field is to increase the dislocation velocity. The present work is also based on this influence of magnetic field to a deforming body.

## 2.3 Adhesive Wear

### 2.3.1 Junction formation & metal transfer

When two clean surfaces are brought together under a normal load the atoms must come into contact at some points and therefore interatomic forces come into operation. All real surfaces consist of surface irregularities when examined at microscopic level. The surface irregularities have the features of waiviness and roughness. Due to this unevenness of the surfaces, the contact between two solids is not at all points. Rather the contact is initiated at those points which are nearest to each other. Therefore, these contacts occur only at few isolated points. Thus the load is being supported only by a small portion of the total nominal area of contact. The area associated with the peaks which are supporting the load is therefore called the real area of contact, $A_r$ between the two solids. As the load is increased the peaks get first elastically deformed and subsequently they suffer plastic deformation. And a finite real area of contact is established.

These small areas where the actual contact is occuring are generally called as asperities. It is thus well accepted in the study of friction and wear that the actual area of contact between two solids occurs at such asperities only.

The real area of contact is seen to be only a small fraction of the apparent (nominal) area of contact and therefore the load is actually supported by a very small area $A_r$.

$$A_r = \sum_{i=1}^{n} A_i = \frac{N}{H} \tag{2.10}$$

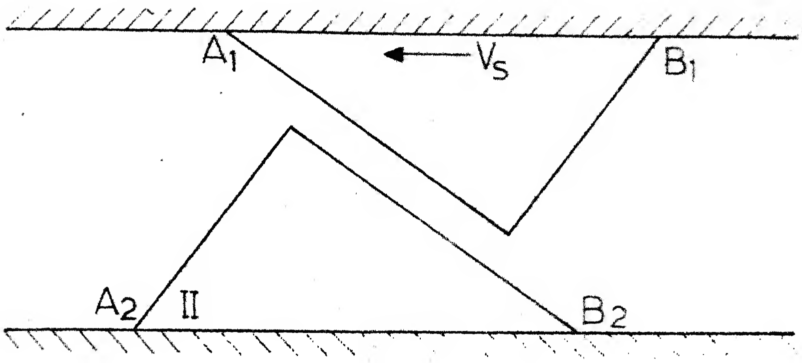
where $A_i$ = Area of the ith deformed asperity

$n$ = total number of asperities under deformation

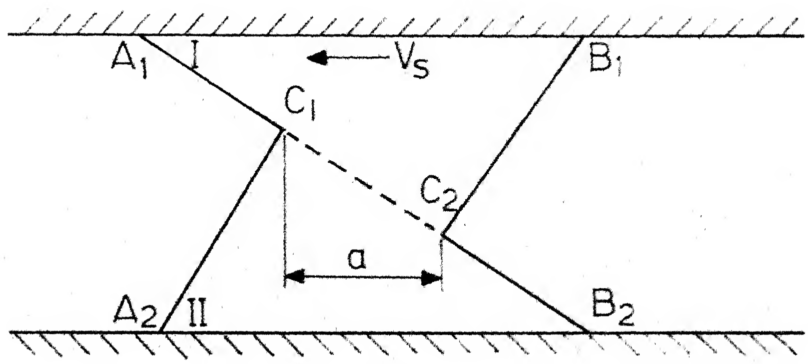
$N$ = load

$H$ = hardness of the softer material.

In the rubbing of two solids such deformation of the asperities is a continuous phenomena. And, if the conditions of pressure, temperature and surface behaviour are conducive to the adhesion of two mating bodies, a kind of metallic bond gets developed. Thus, a kind of bonded junction gets formed. When these two bodies are sliding relatively, these junctions get broken. The process of contact of asperities, their formation of the junction and subsequent deformation and failure is the basic reason for the adhesive wear.




(a)

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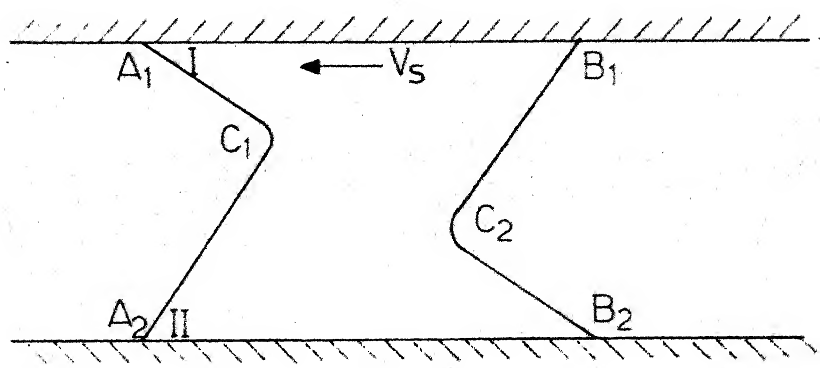



(c)

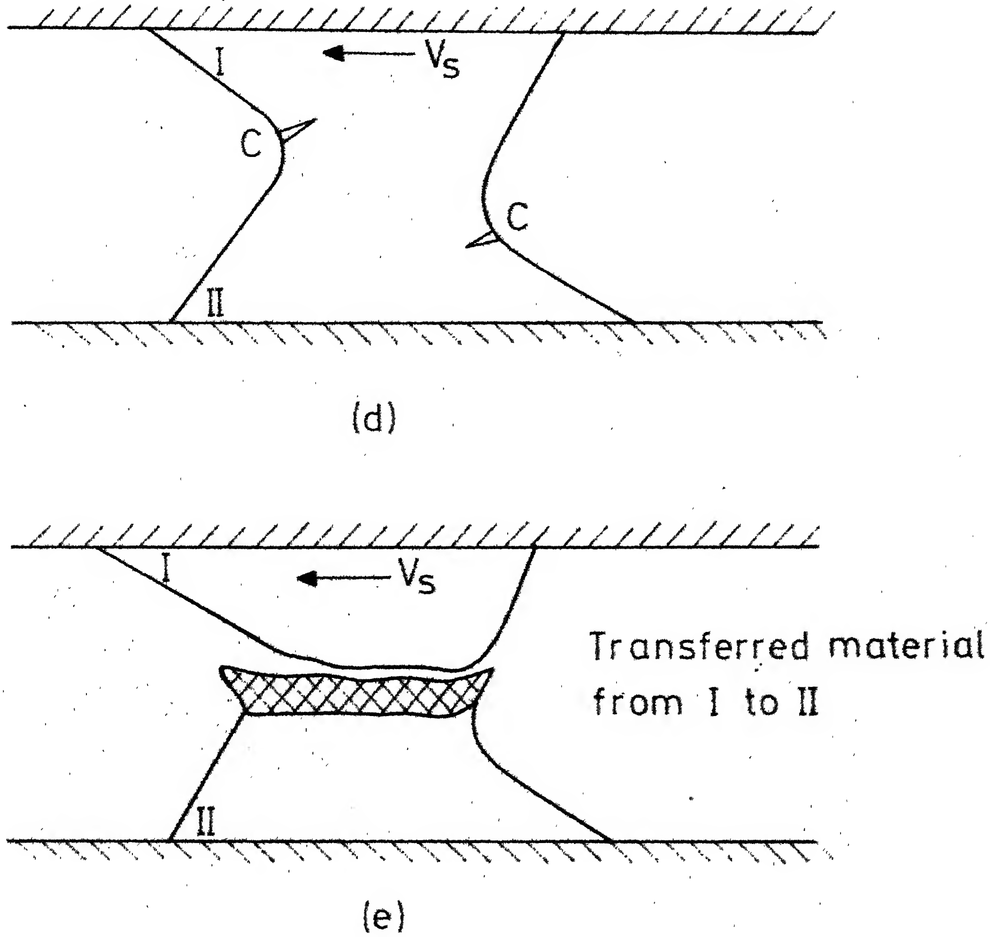



FIG. 2 FRACTURE OF A SLIDING ASPERITY JUNCTION

The stages through which junctions have been observed to be passing can be understood with the aid of Figure 2. The figure illustrates the deformation of asperities I and II of similar hardnesses. After initial adhesion most of the centre of the junction is sheared uniformly; Figure 2.c. Due to this shearing the interface gets stretched. This would help to break any surface films present and thereby strengthen adhesion. As the tendency for the asperities to pass each other continues an intermediate stage shown in Figure 2.d is reached, when the junction has acquired a symmetric shape. Since the adhesion is assumed to be fairly strong the junction deforms as a single body and thus necking and fracture occurs in the most critically stressed region of the junction. In this manner a small particle is transferred from one asperity to the other one. In a subsequent encounter this transferred material may become a loose wear fragment. Experiments have shown that most of the times the softer asperity looses material to the harder one but the probability of harder body loosing material is also finite and can be substantial. The reason for this is the presence of weak spots within the harder asperity as well as its fatigue caused by the interactions. In general, therefore, the fracture occurs more often on the side of the softer asperity as against that of the harder asperity. The ratio of probabilities also increases as the ratio of hardness increases.

In the present work the effect of the magnetic field is also seen through its effect on such a junction, treated as a single body with notches at $C_1$ and $C_2$ (Fig. 2).

2.3.2 Crack Initiation and Wear

Stroh [19] showed that obstacles, where dislocations pile up, offer possible nuclii for the initiation of a crack in a body. The obstacle can be a grain boundary, second phase particle or an immobile groups of dislocations. The number of dislocations that can be supported by an obstacle depends upon the type of the barrier, structural features at the barrier, the material and the temperature. The break down of a barrier, in general, can occur by slip on a new plane by climb of dislocations around the barriers or by generation of high enough stress to produce a crack.

The role of dislocations near the rubbing surfaces has been discussed by several people [20, 22]. Warren [22] has investigated the possibility of clustering of dislocations beneath a surface notch. He has shown that notch creates a major effect, attracting dislocations towards it. This, therefore, should lead to accumulation of dislocations at the notch or the crack tip. Figure 3 shows two cases considered by Warren. In these figures the line segments show the magnetitude and the direction of the

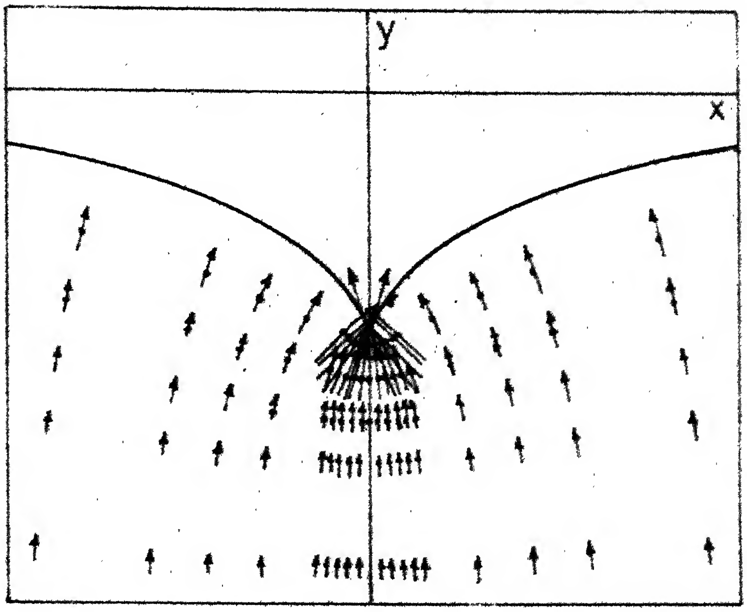



Fig. 3 a -Edge dislocation force. (22)

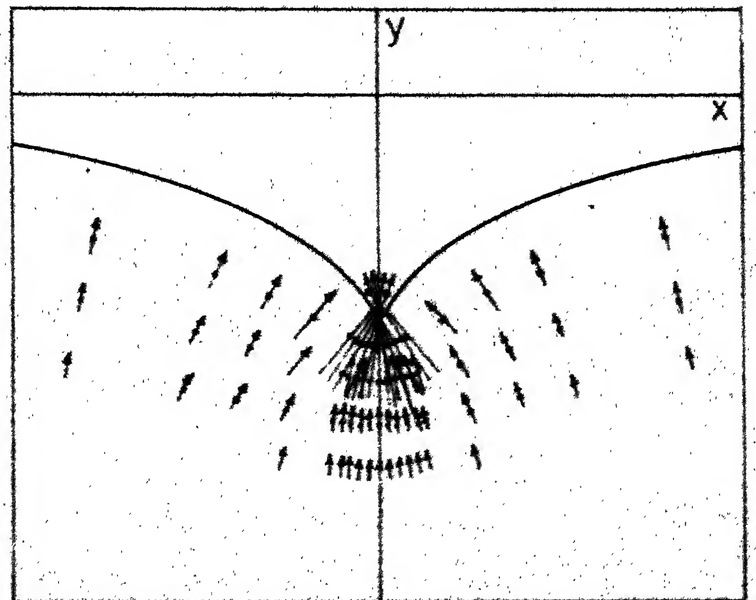



Fig. 3 b -Screw dislocation force. (22)

**Fig. 3 Agglomeration of dislocations at the notch**

force acting on a dislocation located at the position of the directed line segment. It appears, therefore, that if these dislocations become mobile, say, when a large stress is applied these should agglomerate at the notch. Also, since the piling up of dislocations can initiate a crack at such a point in the matrix, such agglomeration would increase the probability of crack initiation at the notch. Muju and Ghosh [6 - 9] proposed that this agglomeration of dislocations at the notches may be utilized to explain the fracture and thus the wear characteristics at the asperity junctions. This is explained as follows.

In a plastically deforming ferromagnetic body the rate of arrival of dislocations at the notch would be dependent on their velocity and hence, on the magnitude of internal stresses. When a strong magnetic field is applied to such a body, the mobility of dislocations is enhanced considerably as discussed in section 2.2. Consequently, it is expected that the agglomeration of dislocations at the notch would be more intense. Thus the failure characterstics at the notch would be different.

In the present work body I is a ferromagnetic body and when a magnetic field is applied the velocity of dislocations in it get enhanced. In asperity junction the agglomeration of dislocations on the side of asperity I will be faster than on the side of asperity II. This

increases the frequency of failure on side of asperity I compared to that of side of asperity II. Thus, during a given period of time junction should therefore fail more often on the side of asperity I than on the side of asperity II. This leads to the conclusion that the application of magnetic field increases the wear rate of body I (body with higher permeability in case of two ferro-magnetic bodies) and consequently reduces the wear rate of body II. This increases in wear rate of body I is further discussed in the following Chapter.

# CHAPTER III

## ADHESIVE WEAR IN PRESENCE OF MAGNETIC FIELD

### 3.1 Complimentary Nature of Adhesion Wear

In the previous chapter the formation of an adhesive bond has been discussed. In the case of an ideal adhesion, a negative free energy of the bond formation must exist. The strength of the bonding at the point of adhesion is often so great that while attempting to free the surface, separation may not take place along the original surface. The bond might fail in such a manner that the fracture occurs in one of the bodies resulting in metal transfer and subsequent removal.

The primary cause of this transfer, according to Burwell and Strang [23], Archard [24], etc. is due to the formation of welded junctions and their subsequent destruction. Burwell and Strang derived a relationship between wear volume w, sliding distance L and normal load N for average normal pressure less than one third of hardness of softer material as

$$w = C \frac{NL}{P_m} \tag{3.1}$$

where, C = constant, defined as the probability of atom removal

$P_m$ = Flow pressure of the softer body.

For average pressure greater than one third of hardness as

$$h = C \frac{PL}{P_m} \tag{3.2}$$

where, $h$ = depth of wear

$P$ = average normal stress over the nominal contact area.

They proposed that the energy required for the wear volume removed can be obtained from the friction work. In their understanding of the process they considered that the size of the wear particles need be same. Work of Archard [24] showed that the size need not be the same and he experimentally verified the Burwell's theory.

The precise nature of the mechanism of particle removal is difficult to describe because in all probability a number of processes can take place. However, under the influence of the temperature gradient and of stresses and concentration produced during sliding, atoms may diffuse from one material in to the other causing corresponding increase or decrease in the weight concentration of the elements in the bodies. With this as basis from the Trigger and Cho's [25] mechanism of wear, the wear was found to be most approximately related as

$$\frac{W}{LN} \propto \frac{1}{H} \exp. \left( \frac{-u}{R\,\theta} \right) \tag{3.3}$$

where, $u$ = Diffusion activation energy of wear

$R$ = universal gas constant

$\theta$ = temperature of sliding.

In terms of sliding velocity $V_s$, the wear volume rate W as given by Cook and Nayak [26] is

$$\frac{W}{LN} = \frac{V_s N Z}{H}$$

$$= \frac{V_s N Z_o}{H} \exp. \left( \frac{-u}{R \theta} \right) \qquad (3.4)$$

Here Z is known as wear coefficient. When the two contacting members try to slide past each other a force of friction arises from the need to break the junctions in shear. From the discussion presented in preceding section, it is clear that the asperity junction can fail on either side of the junction. Also, since in a given period of time, a definite amount of material is generally lost by both the bodies at all velocities, it is apparent that the adhesive wear does take place. Thus when ever an adhesive wear is occuring, equations like 3.3 and 3.4 would give the wear rate for the corresponding body for a given set of conditions.

Experiments on single body junctions have been conducted [27] and no preferential cracking on either side of the junction has been observed. The cracks have simultaneously initiated and propogated on both sides of the asperity junction. However, in a bimetallic junction this

does not happen so. The crack does not simultaneously initiate in both the bodies. Thus in a given period of time if there are certain number of fractures of the junctions on one body, it should correspond to a definite loss of material from that body. This would represent the wear rate in adhesion. Similarly, if during the same period of time junctions fail on the side of the other body, then this would also be losing some material. It is the property of the sliding material that decides upon the number of fractures that take place in body I or the body II. Logically it should depend on strength, surface properties, fracture characterstics, etc. which are generally temperature dependent. Therefore the relative wear of two bodies should also be a function of interface temperatures and hence rubbing velocity.

For a given number of junctions if the probability of failure on either side is enhanced, the number of fractures on the other side will naturally get reduced during the same period of time and vice versa. Therefore when adhesive wear is occuring there is a complimentary behaviour exhibited in the total wear. That is if one body shows an increase in wear rate, the other body would show a decrease in wear rate as long as adhesion wear is taking place.

For instance, if a rubbing operation involves 'n' number of asperity junctions, we can write

$$n = n_I + n_{II} \quad (3.5)$$

where $n_I$, $n_{II}$ = Number of asperitics fracturing on the side of body I and body II respectively.

It is possible that the values of $n_I$ or $n_{II}$ may get changed due to the change in the wear conditions. But there will be a corresponding change in $n_{II}$ or $n_I$ as the case may be. This mechanism can be understood as complimentary nature of adhesive wear. The effect of magnetic field on such a wear can be seen in the following section.

## 3.2 Dislocation Enhancement at the Asperity Junction

Effect of magnetic field on adhesive wear seems to have been first studied by Muju and Ghosh [6, 8]. According to them the rate of accumulation of dislocations at the notch formed at the junction is shown approximately obtainable as

$$\rho^{o}(t) = \rho_o \left\{ 1 + \frac{V_o\, t}{r_i^{\,2}} \left( 2\, r_i + V_o\, t + \frac{1}{\sqrt{\rho_o}} \right) \right\} \quad (3.6\text{ a})$$

$$\rho^{H}(t) = \rho_o \left\{ 1 + \frac{V_H\, t}{r_i^{\,2}} \left( 2\, r_i + V_H\, t + \frac{1}{\sqrt{\rho_o}} \right) \right\} \quad (3.6\text{ b})$$

where, $V_o$, $V_H$ = The uniform dislocation velocity in the absence and presence of magnetic field,

$\rho^{o}(t)$, $\rho^{H}(t)$ = Dislocation densities on the side of I in absence and presence of magnetic field,

$r_i$ = radius of the elemental area at the notch,

$\rho_o$ = initial uniform dislocation density at the notch.

Based on the property of dislocations nucleating a crack, they argued that the probability of failure on a particular side should depend upon the dislocation density on that side of the junction. If body I is considered to be a ferromagnetic and body II non-magnetic, the agglomeration of dislocations on the side of body I (ferromagnetic) will be much faster than on the side of asperity II (non-magnetic). This is because the magnetic field enhances the velocity of dislocations only on the side of the asperity I and has no such effect on the asperity II. When both the asperities are ferromagnetic in nature, the one with a higher permeability would represent asperity I, of Figure 2.c. The discussion on the crack initiation at the asperity junction could still proceed in the same manner as for the junction formed by a ferro-magnetic and a non-magnetic body. In both the cases, application of an external magnetic field leads to an increased dislocation density on the side of the asperity I compared to that on the side of asperity II. Therefore, taking recourse to the earlier discussion, in section 2.3.2, the application of the magnetic field can lead to increased probability of failure of the junction on the side I and correspondingly to a decreased probability

of failure on the side of II provided the duration of the time considered is less than $t_0$. (The time required for a junction to form and break, when no magnetic field is applied across it). Thus, during a given period of time, junctions should fail more often on the side of asperity I than on the side of asperity II. This leads to an important conclusion that the application of an external magnetic field should increase the wear rate of body I and consequently reduce the wear rate of body II. To analyse it further, the gain factor G may be redefined as

$$G = \frac{W^O - W^H}{W^O} \qquad (3.7)$$

where, $W^O$ = volume of wear in time T, when no magnetic field is applied,

and $W^H$ = volume of wear in time T in presence of magnetic field.

On the basis of the preceeding observations the gain factor G should turn out to be a negative quantity for the ferromagnetic body, I. On the same reasoning G should turn out to be a positive quantity for the non-magnetic body, II. In brief, body I should show a negative gain, while body II a positive gain when they are sliding in presence of the magnetic field. The magnitude of this positive or negative gain should obviously depend upon the relative enhancement of the dislocation density caused by the application of

the magnetic field. An expression for such enhancement is shown in equations 3.6 a and 3.6 b.

Using these equations the enhancement of dislocation density on the side of body I can be calculated as

$$\delta\rho = \rho^{H} - \rho^{o} \qquad (3.8)$$

Muju and Ghosh [6] have shown that variation of $\delta\rho$ with rubbing velocity is of the form shown in Fig. 4. Since $\delta\rho$ would be controlling the fracture rate on the side of body I, the same curve would also represent the gain factor G (represented as $G_I$ for body I). Obviously, therefore when body I is a ferromagnetic and body II is non-magnetic the gain curve (G vs $V_s$) would be as shown in Fig. 4.

From the arguments presented in this and preceding section, it turns out that if brass is rubbed against a mild steel body, then mild steel (body I) should lose more material in presence of magnetic field compared to its rate of wear when no magnetic field is applied. Also, as long as, the adhesive wear is prevailing this should result in reduced wear rate of brass (body II) in presence of magnetic field. This means that the gain factor $G_I$ and $G_{II}$ would be negative and positive as shown in Fig. 4. Muju [8] has done extensive experimentation on rubbing of ferromagnetic bodies (iron, nickel and mild steel) against non-magnetic bodies. In every case he found that

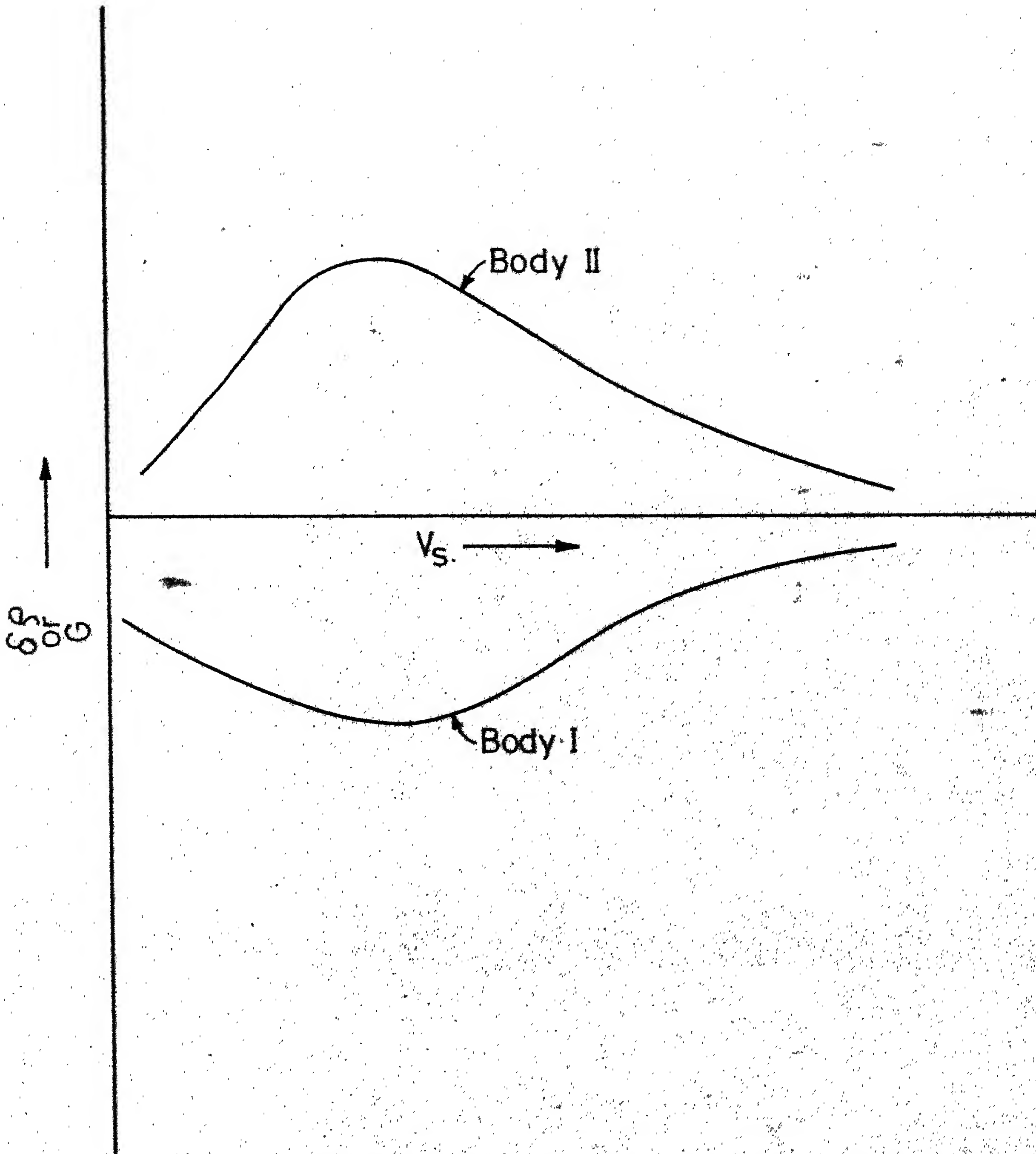



Fig. 4 - Diagram showing trend in the densities of dislocatio
at the notch under magnetic field for body I and boc

indeed the ferromagnetic body lost more material in presence of magnetic field. The gain factor $G_I$ is found to be negative at almost all the velocities in the range 10 to 150 m/min. The trend has agreed with Fig. 4. However, the gain factor $G_{II}$ for brass was not found to be positive at all speeds. It was observed that beyond a certain speed the gain factor of mild steel (body I), $G_I$ and brass (body II), $G_{II}$ is negative. This change in the gain factor of brass (body II) forms the subject for the following sections.

### 3.3.1 Effect of magnetic field on diffusivity

In the expression for wear rate $W$ given by

$$W = \frac{Z_o N V_s}{H} \exp.\left( \frac{-u}{R\,\theta} \right) \qquad (3.4)$$

where $u$ represents the activation energy for wearing process. This equation can be rewritten as

$$\ln \frac{W}{V_s} = \ln \left( \frac{Z_o N}{H} \right) - \frac{u}{R} \frac{1}{\theta} \qquad (3.9)$$

If a wear experiment is conducted and $\ln \frac{W}{V_s}$ is plotted against $\frac{1}{\theta}$ the result should yield a straight line if wear mechanism is that of adhesion. For a constant value of $N$ and $H$ the slope of the straight line is given by $\frac{u}{R}$. This procedure can in fact be used to check i) whether the wear mechanism is through adhesion and ii) to obtain the value of activation energy involved. Using this procedure Cook [28] has found the value of the activation

energy for some grades of mild steel to lie between 40000 to 50000 cal/mole.

In the present work it was found useful to do similar analysis. Accordingly the wear results obtained as shown in Table 3.1, for mild steel rubbing against brass were checked in this manner. The results are shown in figure 5. In this figure wear volume rate per unit sliding distance is plotted against $1/\theta$ for both magnetised and nonmagnetised state of mild steel body. Here the temperature of the interface $\theta$ of the sliding pair is obtained from the Bowden and Thomas [29] equation given as

$$\theta = \frac{0.236\ N\ V_s\ \mu}{l\left[k_A + 0.88\ k_B\left(\frac{V_s\ l}{K_B}\right)^{0.5}\right]} \qquad (3.10)$$

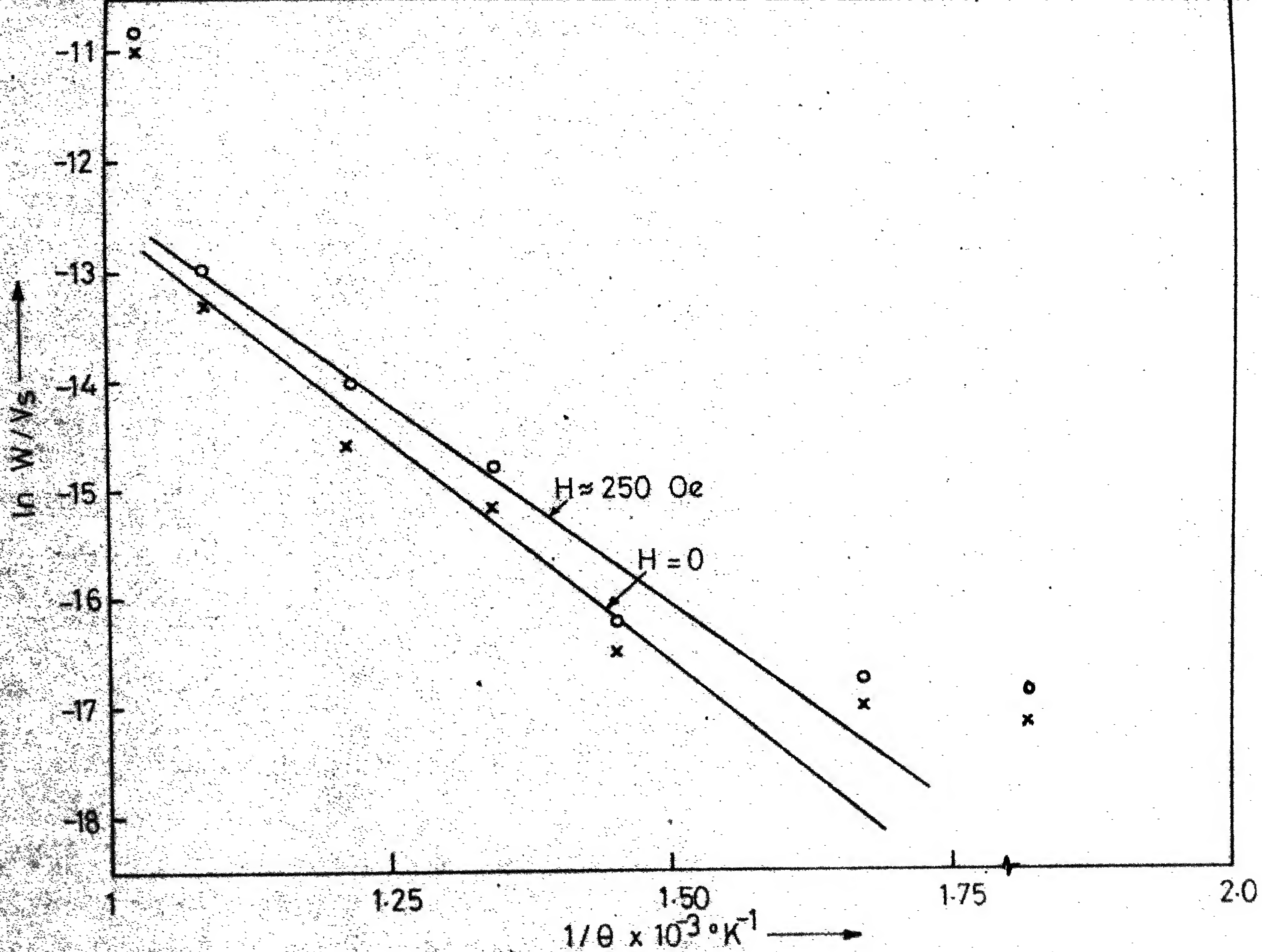
where, $\mu$ = coefficient of friction between the sliding bodies,

$l$ = length of the slider,

$k_A$, $k_B$ = thermal conductivity of slider (A) and body (B) respectively,

$K_B$ = thermal diffusivity of body.

As can be seen from the figure except for the points corresponding to higher values of $1/\theta$ all other points seem to lie on a straight line. This is observed so, for both cases viz. when magnetic field is present and when it is not present. After fitting the best straight



ln W/Vs
-11
-12
-13
-14
-15
-16
-17
-18
H ≈ 250 Oe
H = 0
1
1·25
1·50
1·75
2·0
1/θ x 10$^{-3}$ °K$^{-1}$

TABLE 3.1

Rubbing of Mild Steel Pins Against Brass Cylinder

Feed = 0.05 mm/revolution

Dia. of M.S. Pin = 6 mm

Dia. of Brass Pin = 54 mm

Magnetic Field Strength = 250 Oe

Load = 10 kg

| Rubbing Velocity $V_s$ (m/min.) | Interface temperature $^ok$ | Wear volume rate when magnetic field is not present $W_o$, $10^{-5}$ $mm^3$/min | Wear volume rate when magnetic field is present $W_H$, $10^{-5}$ $mm^3$/min | $\ln \frac{W_o}{V_s}$ | $\ln \frac{W_H}{V_s}$ | $1/\theta$ $10^{-3}$ $^ok^{-1}$ |
|---|---|---|---|---|---|---|
| 8.5 | 420 | 0.019682 | 0.022916 | -19.8230 | -19.6709 | 2.3810 |
| 13.6 | 481 | 0.592077 | 0.818919 | -17.0477 | -16.7233 | 2.0790 |
| 34.0 | 601 | 1.905240 | 3.09004 | -16.7262 | -16.2427 | 1.6640 |
| 55.0 | 690 | 3.62590 | 4.44565 | -16.5347 | -16.3309 | 1.4490 |
| 68.0 | 746 | 16.37020 | 26.11735 | -15.2685 | -14.7993 | 1.3410 |
| 95.0 | 828 | 43.24380 | 77.82950 | -14.6025 | -14.0149 | 1.2080 |
| 120.0 | 922 | 196.03860 | 271.50750 | -13.3247 | -12.999 | 1.0850 |

line using least square method, the slopes are obtained as

Magnetic case $\frac{u}{R} = 7,525\ ^{\circ}k$

Non-magnetic case $\frac{u}{R} = 8,250^{\circ}k$

This gives the value of activation energy as

Activation energy when magnetic field is present, $u_H$ = 15.05 k.cal per mole.

Activation energy when magnetic field is not present, $u_o$ = 16.50 k.cal per mole.

This is a very important result and suggests that the activation energy for wear is less in presence of magnetic field. Therefore the percentage reduction in the activation energy due to the application of magnetic field is of the order of 9. Also, the obtained value of activation energy $u_o$, $u_H$ is close to that of half the bulk diffusion activation energy for iron. It is to be noted that surface diffusion activation energy is generally taken to be approximately half of the bulk activation energy [30]. Thus the results obtained from these calculations suggest that in adhesive wear, the activation energy involved is close to the surface diffusion activation energy.* On the basis of this observation the diffusivity in presence and absence of magnetic fields can be written as

*Another important observation is that the value of activatio energy obtained in the above calculations is close to the value of 19.2 kcal/mole, the value of the diffusion activati energy obtained by Hirano et al. [31] at high strain rates.

$$D_s^H = D_o \exp. \left( \frac{-u_H}{R\,\theta} \right) \tag{3.11 a}$$

$$D_s^o = D_o \exp. \left( \frac{-u_o}{R\,\theta} \right) \tag{3.11 b}$$

In these expressions the subscript s represents that the body is in strained condition. Superscripts H and o denote the presence and absence of magnetic field. It can be seen that the ratio of diffusivity is given by

$$\frac{D_s^H}{D_s^o} = \exp. \left( \frac{u_o - u_H}{R\,\theta} \right)$$

$$= \exp. \left( \frac{\Delta u}{R\,\theta} \right) \tag{3.12}$$

$\Delta u$ is the decrease in the activation energy by the application of magnetic field. Obviously the diffusivity of the ferromagnetic body is enhanced several times.

It is pointed out that Muju and Ghosh [7 - 9] have done a static diffusion test (when no deformation was occuring) both in presence and absence of the magnetic field and no change in diffusivity was observed. This was ofcourse in agreement with their theoretical reasoning. They have however postulated an increase in the diffusivity due to the magnetic field when the plastic deformation is prevailing. They believe that since there is a large amount of dislocation density at the asperity junction this should lead to large amount of vacancy formation and hence to the increase in diffusivity. Since the magnetic field

would increase the dislocation velocity and hence the dislocation density at the asperity junction the generation of vacancies would be further enhanced by the application of magnetic field. Using the arguments of Hirano et al.[31] they have shown that the ratio

$$\frac{D_s^H}{D_s^o} = \frac{\rho^H}{\rho^o} \qquad (3.13)$$

Experimental [31 - 33] as well as theoretical [34 - 36] investigations clearly indicate that diffusion in metals is significantly enhanced during deformation. However it is at present not clear whether this enhancement is due to the generation of excess vacancies during deformation or because of some other source such as the inhomogeneous nature of plastic deformation. Thus while there is a disagreement about the source of enhancement, it is well accepted that there is an enhancement in diffusivity due to plastic deformation.

There is a qualitative evidence from direct electro-microscope observation that the diffusion takes place rapidly along the dislocations [37] . The results indicate in general that the diffusion occurs along dislocations at rates many orders faster than through the lattice. In silver for instance, it has been shown that

$$\frac{D_P}{D_{T_o}} \approx \exp . \frac{0.55\ u_L}{k\ \theta} \qquad (3.14)$$

where $D_P$ = diffusivity along the dislocation pipe or core,

$D_{T_o}$ = diffusivity in dislocation free lattice,

$u_L$ = activation energy for lattice diffusion.

At temperatures of 467 °c, $\frac{D_P}{D_{T_o}}$ is of the order of $10^7$. Because of the fact that the dislocation contents increase appreciably during deformation, it is logical to believe that the high value of diffusivity in the dislocation core would also enhance the average bulk diffusion rate during plastic deformation. Hart [38] has derived an expression for the enhanced average bulk diffusion in a crystal containing a large number of dislocation pipes. Hart's relation leads to

$$\frac{D_T}{D_{T_o}} = \text{function of } \left( \frac{D_P}{D_{T_o}} \right) \qquad (3.15)$$

where, $D_T$ = average bulk diffusivity.

Ruoff and Balluffi [34] have shown that the equation 3.15 is valid as long as the following condition is satisfied

$$2 \left( D_{T_o} t_o \right)^{1/2} > l_d \qquad (3.16)$$

where, $t_o$ = experimental diffusion time,

$l_d$ = average distance between two dislocations.

It has already been pointed out that during the deformation of an asperity junction, there would be a very large dislocation interaction. It is possible to believe that the enhancement in the bulk diffusivity may be really through the dislocation movement.

Since the application of magnetic field would enhance the movement of dislocation at the asperity junction it can be concluded that there should be a significant enhancement in the diffusivity due to the application of magnetic field. Thus the reduction in the activation energy of wear shown by equation 3.12 might very well be the manifestation of this mechanism.

### 3.3.2 Effect of diffusivity on hardness gradient and wear

It is important to observe that the enhanced diffusivity is expected to lead to greater mass transfer across the interface. This should influence the adhesion wear of the mating surfaces in significant manner. In this connection variation of hardness in the direction normal to the interface seems to be of much significance. Muju [8] analysed the influence of hardness gradient on wear in the manner described in Appendix 1. The hardness gradient at the asperity interface affects the strength of surface layer. The relative change in the strength of the surface layer (along with bulk properties) also play an important role in the process of material removal. This can be further explained as follows.

Consider again two asperities having got firmly bonded together as in Figure 6. If the adhesion bond strength between the surfaces of I and II is lower than the strength of the underlying layer a positive gradient in the mechanical strength exists. Mathematically, $\frac{d\,H(x)}{dx}$ is a positive quantity for this situation, where H (x) is the hardness in the direction normal to the interface. When a positive gradient in the mechanical strength exists the deformation is confined to the surface layer. When the junction fails the failure is confined to the

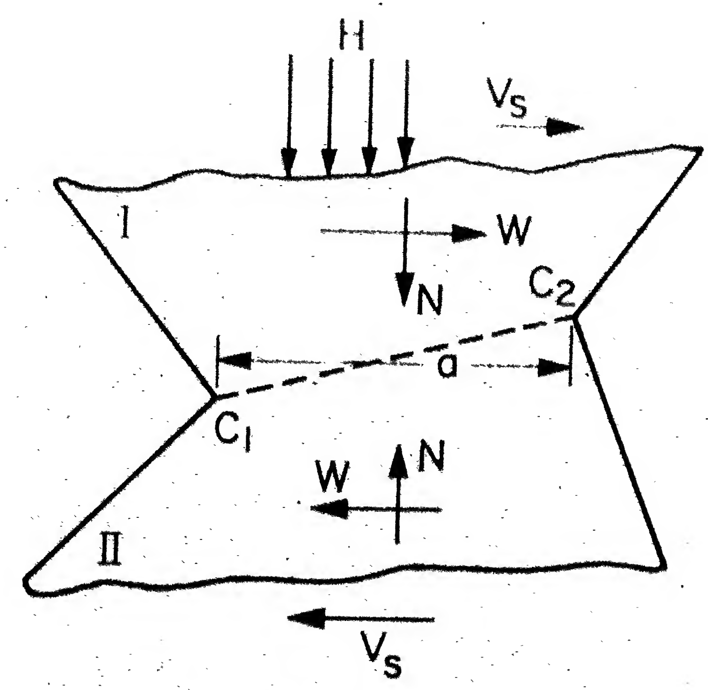



Fig.6-Model Of An Asperity Junction

surface layer. Thus, the friction and wear characteristics are controlled primarily by the characteristics of the surface layer, in this case.

However, when the strength of the bond is greater than that of the bulk material, $\frac{d\,H\,(x)}{dx}$ is negative. Deformation in this case will be extended to larger volume of material. In this case the failure of the asperity junction occurs at a considerable depth below the interface. Thus friction and wear characteristics in this case are controlled by the bulk properties of the materials rather than that of the surface layers.

Figure 7 illustrates how different hardness gradients result in different deformation zones at asperities. Figure 7 a illustrates the case of positive hardness gradient from interface to bulk. The zone of deformation is shown confined to the surface layer itself. Figure 7 b shows the case of negative hardness gradient. The deformation zone is considerably larger than in the first case.

In the present work mild steel (body I) is harder than brass (II). Therefore it is obvious that diffusion of mild steel in to brass would result in a negative hardness gradient in the surface layer of body II. Diffusion of brass in to mild steel may also

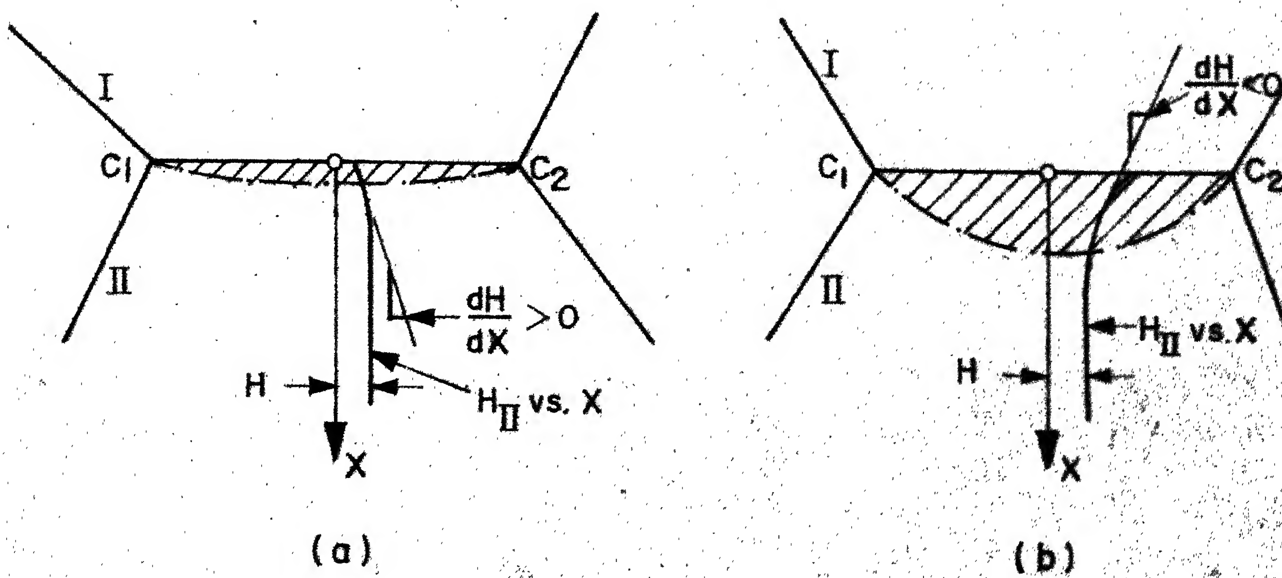



Fig. 7 (a) Case Of a Positive Hardness Gradient. Deformation Is Confined To The Surface Layer.

(b) Case Of a Negative Hardness Gradient. Deformation Is Extended To a Larger Volume.

occur. This can result in a positive hardness gradient in the mild steel which will however, not be much influenced by the application of magnetic field. Muju [39] has, examined such a case of cross diffusion across an interface. He has shown that the net flow of material in such case would occur from body I (ferro magnetic) to body II (non-magnetic) when magnetic field is applied. The negative hardness gradient developed in II, due to diffusion would change, if an external magnetic field is applied. As discussed in Appendix the increased diffusivity would lead to greater depth of surface layer to be detached from body II. This would lead to increased wear rate of body II and this is indeed realised experimentally and discussed in next chapter.

# CHAPTER IV

## EXPERIMENTAL RESULTS AND DISCUSSIONS

### 4.1 Introduction

Previous workers have conducted experiments with a variety of magnetic materials rubbing against some non-magnetic materials and very interesting results have been published [6 - 13]. In order to understand the scope of application of magnetic field which could fortify the theoretical postulates, it was found necessary to conduct some new experiments. Accordingly the following wear experiments were undertaken in the present work.

1. Rubbing of mild steel pins against a brass cylinder in presence and absence of magnetic field.
2. Rubbing of brass pins against a mild steel cylinder in the absence and presence of magnetic field.
3. Rubbing of stainless steel pins against a mild steel cylinder in the absence and presence of magnetic field.
4. Elemental analysis in wear particles using a proton induced X-ray emission spectroscopy (PIXEA).

Hardness and the composition properties of the materials used in the rubbing tests were also estimated by standard laboratory procedures and the results are tabulated below.

TABLE 4.1

| Material | Hardness at room temperature | Chemical composition |
|---|---|---|
| Mild Steel | 70 Rockwell-B | 0.12% Carbon |
| Stainless Steel | 25 Rockwell-C | 18.00% Chromium |
| Brass | 43 Rockwell-B | 60.00% Copper |
| | | 38.00% Zinc |

## 4.2 General Features of Rubbing Experiments

General features common to all the wear tests presented in this work are indicated below.

All the wear tests were performed on a H.M.T. lathe (Model LB-25) machine.

The wear tests were always performed against a fresh cylindrical surface. Figure 8 shows the general experimental set-up used in the rubbing tests. Whenever, the job or the tool was to be magnetised a suitable solenoid designed for the purpose was energised. The solenoid was put in series with a D.C. power supply which was adjusted so that a specified current can be passed through the solenoid coil. All wear tests were conducted with in the speed limits of about 10 m/min - 160 m/min. The rubbing time was so adjusted to make the sliding distance same at all the speeds. This is important for analysing the results and to get measurable quantity of

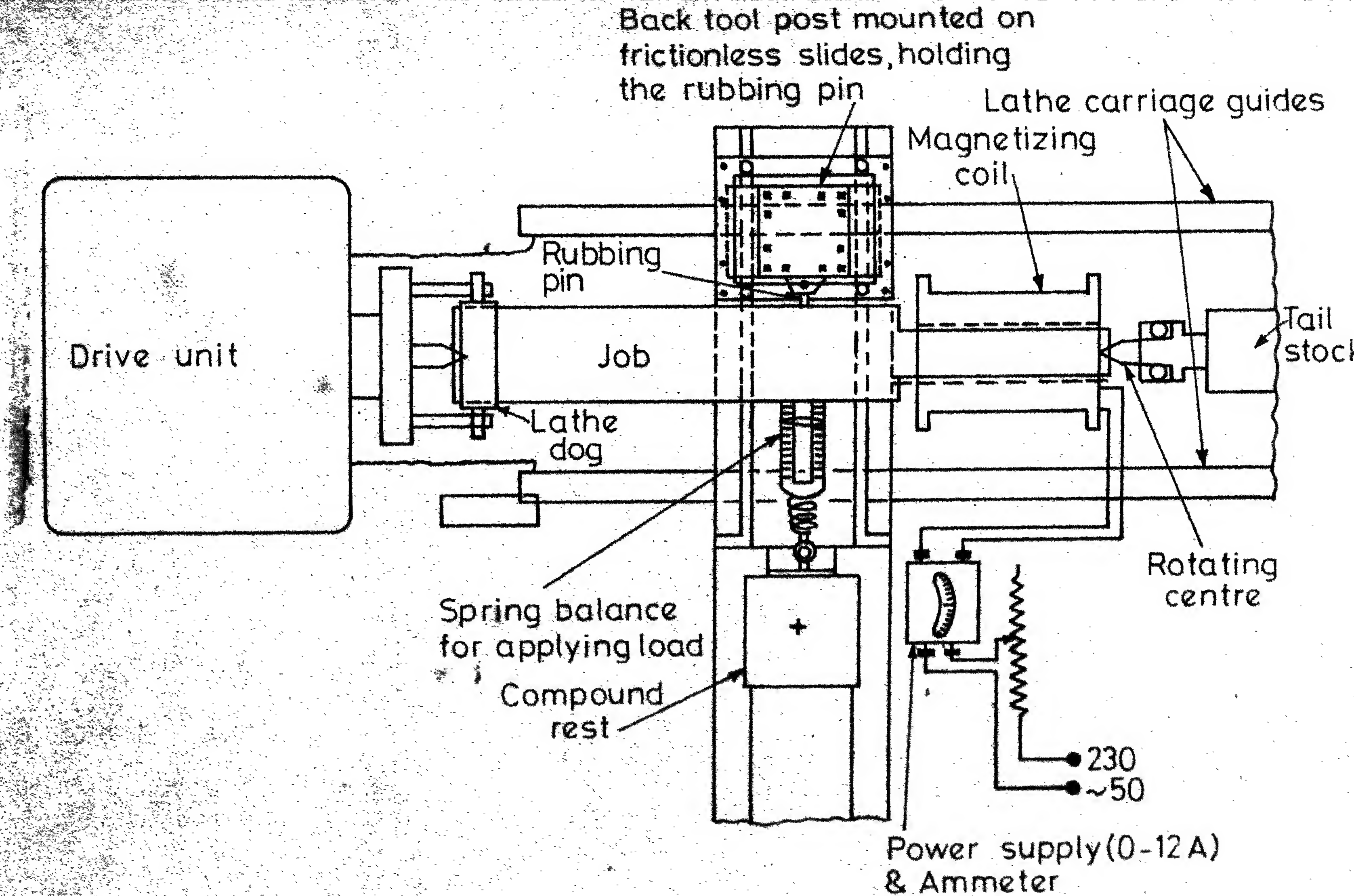
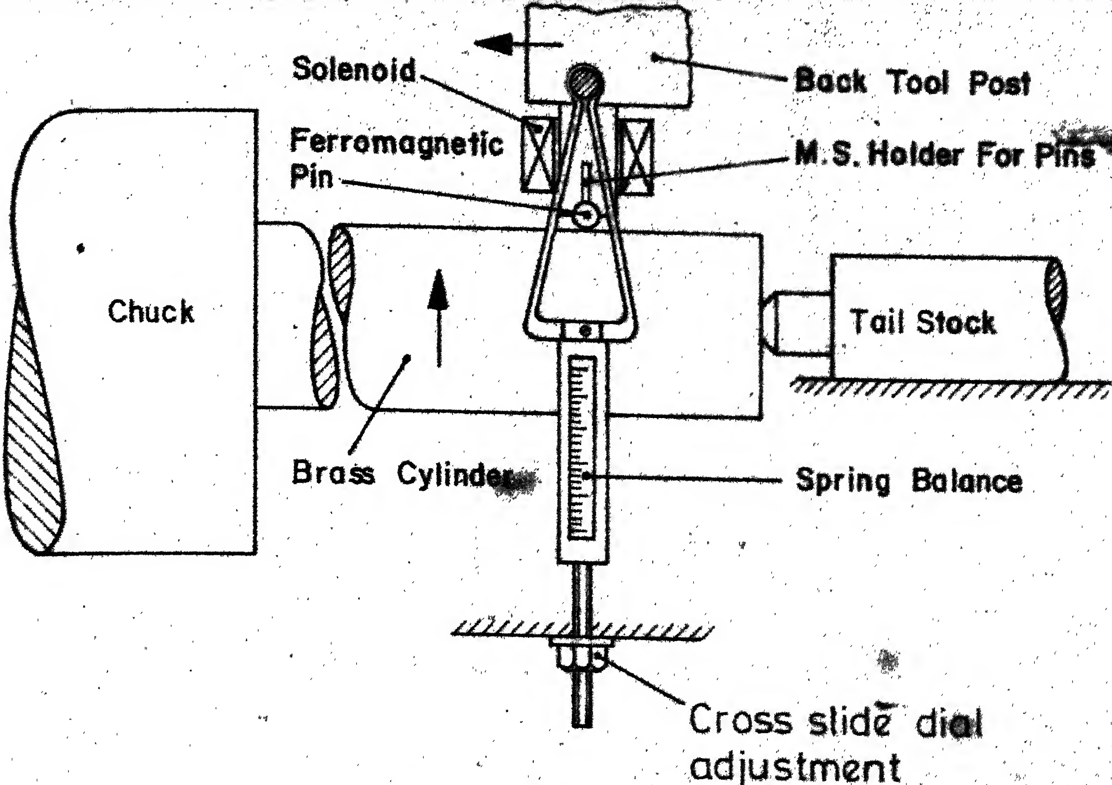
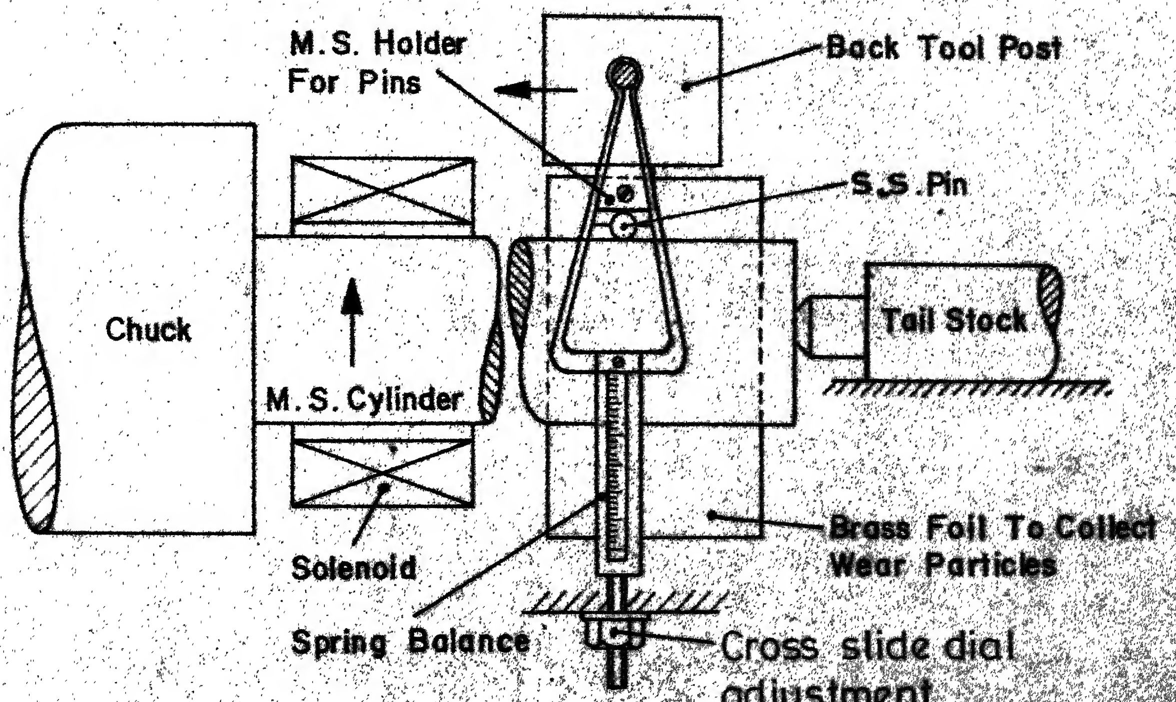



Fig. 8 -Schematic view of the experimental setup for rubbing of non magnetic pins.




(a) Rubbing Of Ferromagnetic Pins Against a Non-Magnetic Body.




(b) Rubbing Of Non-Magnetic Pins Against a Ferromagnetic Body.

Fig. 9 Schematic View Of The Experimental Set Ups For

wear. Also it is expected that the wear takes place steadily atleast during a portion of the rubbing distance. The distance of sliding for all the wear tests was fixed at 100 m.

Measurement of the wear was done with the help of a microbalance in the case of brass and stainless steel pins and a optical projector in the case of mild steel pins.

When the rubbing experiments were performed the load was applied by means of a spring balance as shown in Fig. 9. The insertion and removal of the pins or tools was done by releasing the load and moving the cross slide carrying the tool holder (back tool post). To ensure that the same load has been applied during the rubbing, the springbalance was calibrated with the cross-feed dial of the compound slide. The overhang of the pin from the pin holder and the overhang of the pin holder from the back tool post was maintained the same in all experiments.

For a particular speed, the experiments with the magnetic field were performed after the experiments without magnetic field were completed. When switching over to another velocity the polarity of the power supply was changed so as to remove any residual magnetism from the magnetised body.

Each of the tests was repeated five times and the average value of the 5 readings was taken to plot the wear behaviour. All the experiments (5 in presence of magnetic field and 5 in the absence of magnetic field) were conducted on the same surface for each velocity. This is to avoid the excess or reduced wears due to a change in surface finish of the rubbing surface.

The details about the individual tests are presented in the following sections.

## 4.3 Rubbing Of Mild Steel Pins Against A Brass Cylinder In Presence and Absence of The Magnetic Field

These experiments were performed to understand the variation of gain factor for the ferromagnetic body and to see whether the results are in agreement with the theoretically predicted ones.

In these experiments the pins were mounted firmly in a holder designed for the purpose. The general experimental set-up as that shown in Fig. 8 except that the solenoid designed for magnetizing the tool was used in place of the solenoid used for magnetizing the job. Also, the manner of contact between the pin and cylinder was such that their axes were normal to one another as shown in Fig. 9 a. The rubbing was performed at various speeds and at a feed rate of 0.05 mm/rev. The shape of the wear scar

TABLE 4.2

Rubbing of Mild Steel Pins Against Brass Cylinder

Feed = 0.05 mm/revol.

Magnetic Field Strength = 250 Oe

Dia. of M.S. Pins = 6.0 mm

Load = 10 kg

Dia. of Brass Cylinder = 54 mm

| Rubbing Velocity $V_s$ m/min. | Time of Rubbing min. | Wear of the Pin when magnetic field is zero $d_o$, mm | Wear of the pin when magnetic field is applied $d_H$, mm | Gain factor $G_I$ |
|---|---|---|---|---|
| 8.5 | 12 | 4.8288 | 5.1648 | -0.309 |
| 13.6 | 7.3 | 6.8795 | 7.4591 | -0.382 |
| 34.0 | 2.9 | 3.6604 | 4.1308 | -0.622 |
| 55.0 | 1.8 | 2.6685 | 2.808 | -0.226 |
| 68.0 | 1.5 | 3.2415 | 3.6458 | -0.600 |
| 95.0 | 1.0 | 2.7556 | 3.0830 | -0.560 |
| 120.0 | 0.8 | 3.2160 | 3.4888 | -0.385 |

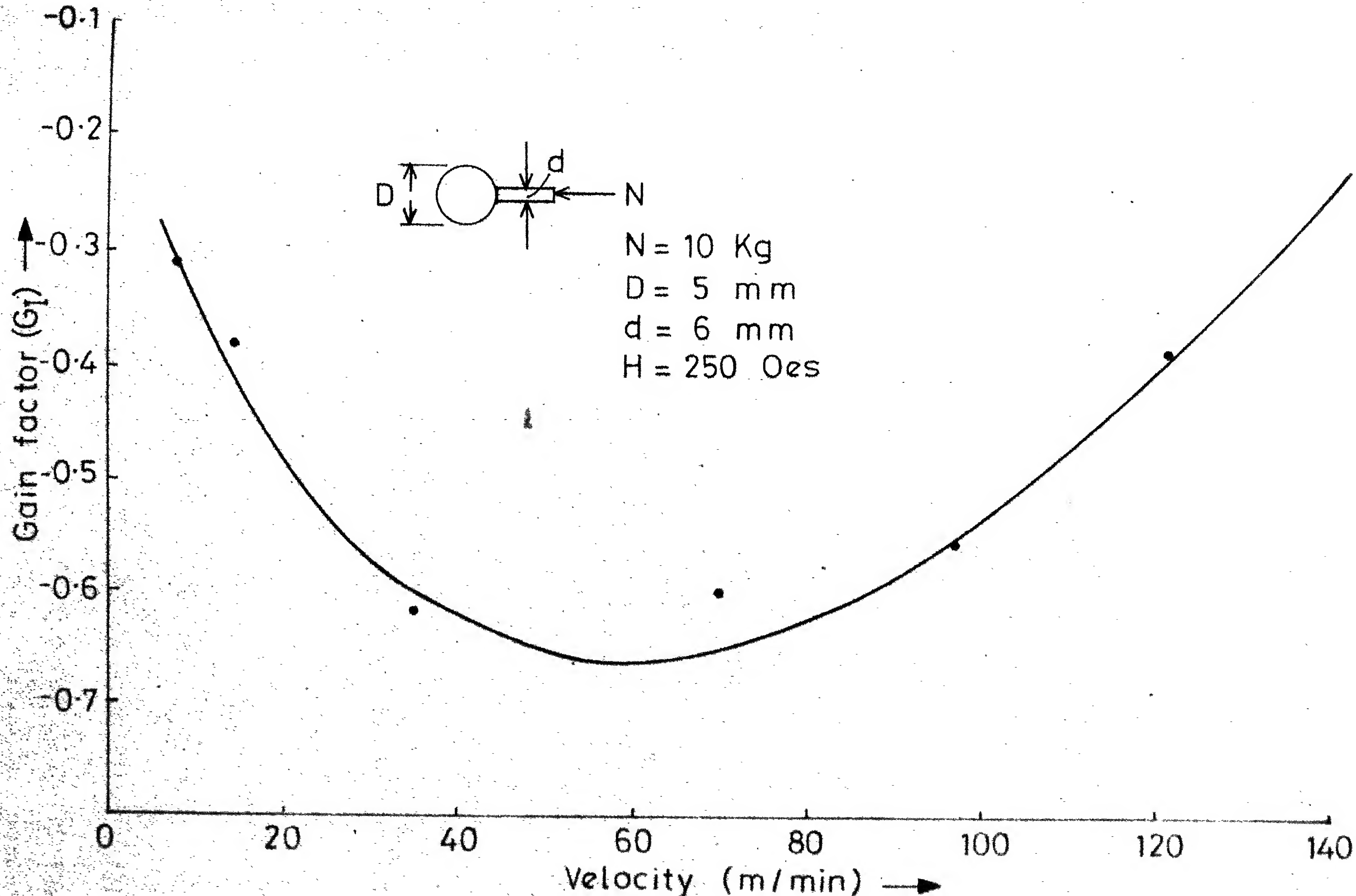



Fig. 10 Variation of gain factor $G_I$ with rubbing Velocity

produced on these pins was elliptical. The volume of wear removed from the pin in such a contact is proportional to the fourth power of the major axis of the elliptical scar on the pin. The values of the major axis of the wear scar obtained in these rubbing experiments are shown in Table 4.2.

Thus in these experiments the gain factor G was calculated as

$$G = \frac{d_o^4 - d_H^4}{d_o^4} \qquad (4.1)$$

In all these experiments, the gain factor G turned out to be a negative quantity. Also, the variation of G with the rubbing speed has the same trend as seen in the case of mild steel tools rubbing or cutting a brass cylinder or an aluminium job, as reported earlier [8] . This can be seen from Fig. 10. Other features relevant to this experiment are shown in the Fig. 10. The measurement of these wear scars was done on an optical projector having a magnification of 100. The values of the wear volume were used to obtain the actual energy of wear as discussed in section 3.3.1.

### 4.4.1 Rubbing of brass pins against a mild steel cylinder in presence and absence of magnetic field.

As already pointed out in section 3.3.2 the wear rate of a nonmagnetic body should get reduced by the application of magnetic field. It has however been reported [6,8]

that the gain factor for non magnetic body may not be always positive. The present experiments were undertaken to verify and investigate this aspect further.

Brass pins were rubbed against mild steel cylinder. The mild steel cylinder was magnetized by means of a solenoid mounted on it. The details of the experimental set-up are shown in Fig. 8. The wear of the pins is calculated as the difference in weight before and after rubbing. The loss of weight in pins at various speeds and feeds is given in tables 4.3 and 4.4 and plotted in Fig. 11. As can be seen in figure an interesting trend in the gain factor $G_{II}$ was observed. The following observations can be made:

1. Upto a certain velocity, gain factor $G_{II}$ was positive and beyond this velocity the gain factor had a negative value. The gain curves for the two feeds (0.075 mm/rev. and 0.15 mm/rev.) investigated and the curve for 0.05 mm/rev. feed as obtained by Muju [8] shows the same type of trend.

2. Important observation is that absolute value of the gain was always increasing with the feed rate for the investigated feeds. However, the variation for 0.05 mm/rev. show differently, this might be due to some differences in the experimentation.

TABLE 4.3

Rubbing of Brass Pins on Mild Steel Cylinder

Dia. of Brass Pin = 6 mm

Dia. of M.S. Cylinder = 99 mm

Feed of Pin = 0.075 mm/revol.

Magnetic Field (H) = 250 Oe

Load on the Pin = 10 kg.

| S.No. | Rubbing Velocity $V_s$ (m/min) | Rubbing time (min.) | Average wear when $H = 0$ $W_o$ (gms) | Average wear when $H \neq 0$ $W_H$ (gms) | Gain factor $G_{II}$ |
|---|---|---|---|---|---|
| 1 | 19.71 | 5.00 | 0.015019 | 0.012655 | 0.1574 |
| 2 | 38.70 | 2.33 | 0.017087 | 0.010771 | 0.3696 |
| 3 | 61.58 | 1.67 | 0.015416 | 0.011816 | 0.2335 |
| 4 | 76.98 | 1.33 | 0.011204 | 0.011297 | -0.0083 |
| 5 | 98.50 | 1.08 | 0.021897 | 0.023997 | -0.0042 |
| 6 | 154.00 | 0.67 | 0.038777 | 0.048225 | -0.2437 |

TABLE 4.4

Rubbing of Brass Pins on Mild Steel Cylinder

Dia. of Brass Pin = 6 mm Magnetic Field = 260 Oe

Dia. of M.S. Cylinder = 99 mm Load on the Pin = 10 kg

Feed of Pin = 0.15 mm/rev.

| S.No. | Rubbing Velocity $V_s$ (m/min) | Rubbing time (min.) | Average wear when $H = 0$ $W_o$ (gms) | Average wear when $H \neq 0$ $W_H$ (gms) | Gain factor $G_{II}$ |
|---|---|---|---|---|---|
| 1 | 9.85 | 10.00 | 0.011301 | 0.006861 | 0.392 |
| 2 | 38.70 | 2.33 | 0.012450 | 0.006300 | 0.494 |
| 3 | 61.58 | 1.67 | 0.016360 | 0.011270 | 0.311 |
| 4 | 76.98 | 1.33 | 0.012573 | 0.013363 | -0.062 |
| 5 | 98.50 | 1.00 | 0.094502 | 0.116705 | -0.235 |
| 6 | 154.00 | 0.67 | 0.25832 | 0.029265 | -0.133 |

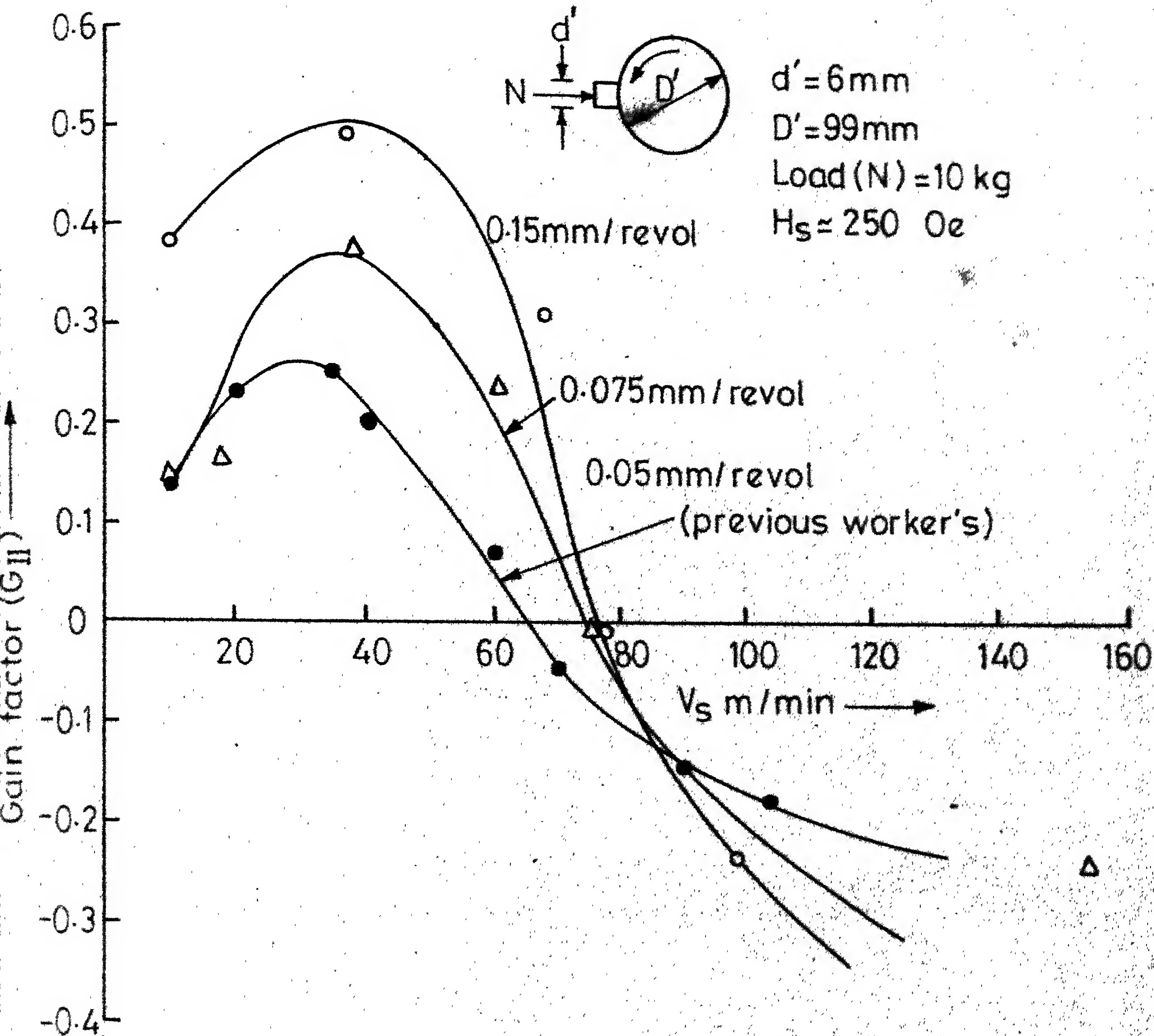



Fig. 11 - Variation of gain factor of brass with velocity and feed.

3. It can be seen that for all the three feeds there is an optimum velocity range at which the positive gain attains its maximum.

4. The critical velocity, $V_c^*$ at which the gain factor becomes zero, for the three feeds shows a very small increase with an increase in feed and hence falls in a small velocity range in the vicinity of 70 m/min.

Two important aspects of this wear behaviour of brass are to be investigated.

1. The increase in positive gain factor, $G_{II}$ with increase in feed before the critical velocity, $V_c^*$ .

2. The increase in the negative gain factor at speeds greater than critical velocity.

The increase in positive gain factor with feed can be explained as follows. The wear rate of brass against steel is different for the case of repeated rubbing and rubbing on a fresh surface. When the brass pin is rubbed against a steel cylinder as in the present case the wear occurs over only in a certain area of contact which can roughly be considered as a circular one. If the feed is greater than or equal to the diameter of the circular contact area, then it would be the case of rubbing on the fresh surface. If, however, the feed is less than the diameter it would be the case of partly repeated and

partly fresh rubbing. The present experiments fall in this category. In the present work the diameter of the contact area is approximately 3 mm. where as the feed rates used are 0.075 mm/rev. and 0.15/mm revolution.

It is evident from the work of Sasada [3] that the wear rate when obtained in fresh surface is greater than that in repeated rubbing. Wear rate for copper rubbing against fresh iron surface is approximately five times that in the repeated rubbing of copper and iron.

In the present work when the feed increases, the area along which the fresh wear occurs is increased. We know that for a given load the total number of asperities n that take part in the rubbing are constant, assuming that all the asperities are of the same size

$$n = \frac{N}{H \ \pi r^2} \tag{4.2}$$

where, $r$ = radius of each asperity

$N$ = normal load.

Since, when the feed increases the area of fresh contact increases, the number of asperities that have fresh encounter are also increased. Therefore, even in the absence of magnetic field the net wear of brass increases considerably, with the increase in feed. In presence of magnetic field, however, the wear of brass increases with increase in feed but not to the extent when there is no

magnetic field. This is because the presence of magnetic field increases the probability of failure of junction on a ferro magnetic body (here mild steel). In fact it can be illustrated with the following simple qualitative estimation that the wear of body I in presence of magnetic field at increased feed is greater than at low feed, at a particular velocity. Hence the gain factor with increased feed is larger.

$$G_I = \frac{W^o - W^H}{W^o} = 1 - \frac{n_I^H}{n_I^o} \qquad (4.3)$$

As shown in Appendix 2 the gain factor for body II, $G_{II}$, can be written as

$$G_{II} = 1 - \bar{\beta}\,(1 + G_I \lambda\,) \qquad (4.4)$$

where $\bar{\beta} = \frac{m_{II}^o}{m_{II}^H}$ (ratio of the mass of wear particles in absence and presence of magnetic field)

Gain factor for body II at feed 1 and feed 2 can be written as

$$G_{II,1}^o = 1 - \bar{\beta}_1\,(1 + G_{I,1}\,\lambda_1) \qquad (4.5\text{ a})$$

$$G_{II,2}^o = 1 - \bar{\beta}_2\,(1 + G_{I,2}\,\lambda_2) \qquad (4.5\text{ b})$$

Suffixes 1 and 2 represent feed 1 and feed 2 respectively.

Since $\bar{\beta}_1$ and $\bar{\beta}_2$ are functions of only diffusivity of body I, it is independent of feed. Therefore

$$\bar{\beta}_1 = \bar{\beta}_2 = \bar{\beta} \tag{4.6}$$

In the present work $\lambda$ is considered to be the ratio of the hardnesses of two bodies which will therefore vary with temperature only. Therefore

$$\lambda_1 = \lambda_2 = \lambda \tag{4.7}$$

The only effect that plays an important role in the variation of $G_{II}$ is the variation of $G_I$ with feed. The interactions taking place in the process control the variation of $G_I$. Since with the increased feed there are more fresh asperities taking part in the process the absolute value of $G_I$ should increase with the feed. Therefore, the ratio of gain factors at feeds 2 and 1 can be written as

$$\frac{G_{II,2}}{G_{II,1}} = \frac{1 - \bar{\beta}\,(1 + G_{I,2}\lambda)}{1 - \bar{\beta}\,(1 + G_{I,1}\lambda)} \tag{4.8}$$

It is known that $G_I$ is negative all along the speed. Thus, when there is an increase in the absolute value of $G_I$ in the numerator of the right hand side of equation 4.8 the ratio $\frac{G_{II,2}}{G_{II,1}}$ can be seen as greater than one. Hence the increase in the absolute value of gain factor with feed is the direct result of the increase in $G_I$ with feed.

4.4.2 Estimation of $G_{II}$ through $G_I$, the gain factor for body I, the interaction factor $\lambda$ and mass ratio of particle $\bar{\beta}$.

4.4.2.a Variation of $\lambda$ with rubbing velocity

In the previous works [6, 8] the interaction factor was considered as a constant. Using a constant

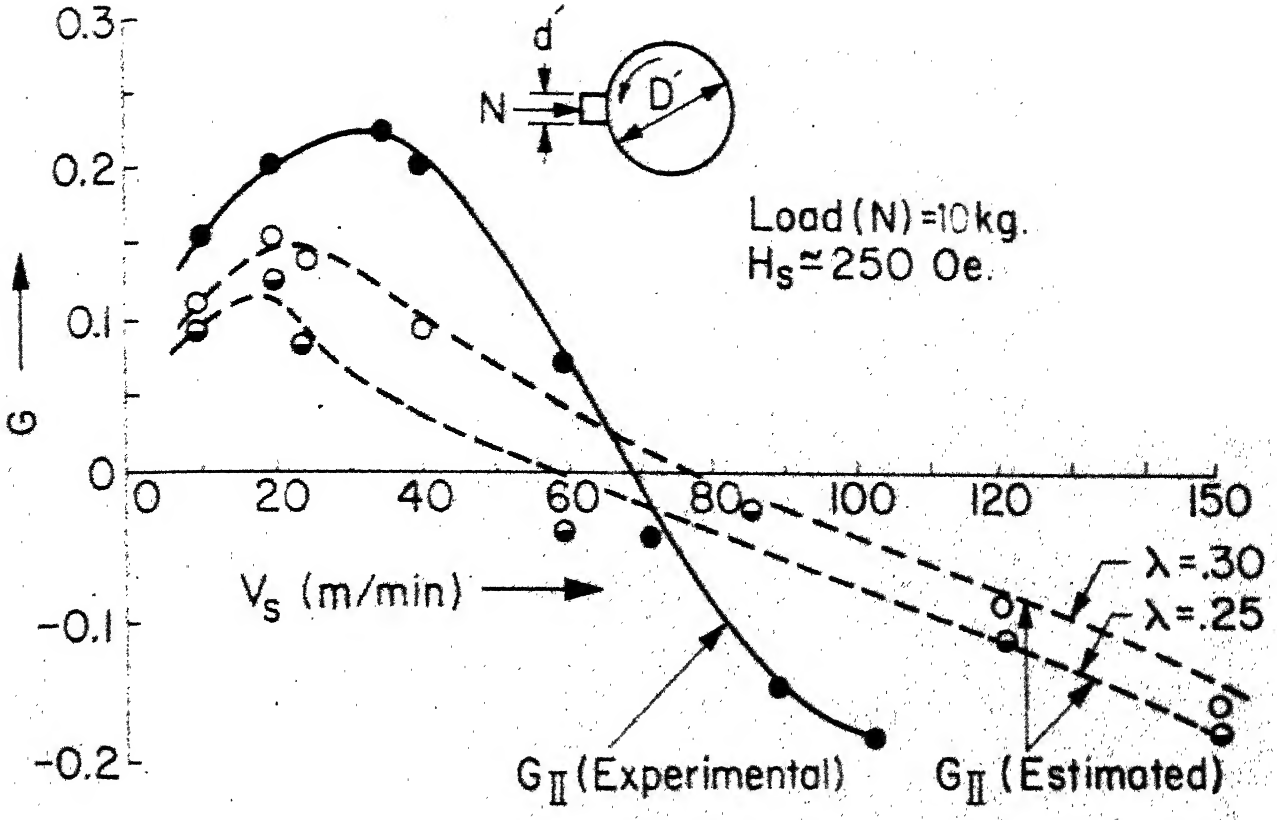



Fig. 12-Variation Of Gain Factor With Rubbing Velocity (Experimental And Estimated)

value for $\lambda$ the estimated theoretical values for $G_{II}$ were not in good agreement (Fig. 12) with the experimental results. It is to be observed that $\lambda$ cannot be a constant and should depend upon the relative strength of the bodies which varies with temperature. Accordingly it was proposed in the present work that $\lambda$ can be, as a first approximation, considered as the ratio of hardness corrected for temperature and strain rate effects. Accordingly $\lambda$ is assumed as

$$\lambda = \frac{H_{II}}{H_I} \left( \frac{1 - \sqrt{\frac{\theta_i}{\theta_{MB}}}}{1 - \sqrt{\frac{\theta_i}{\theta_{MM}}}} \right)^2 \qquad (4.9\ a)$$

where $H_{II}$ and $H_I$ = the bulk hardness of body II and body I respectively,

$\theta_i$ = velocity modified temperature at the interface,

$\theta_{MB}$ = melting point of brass

$\theta_{MM}$ = melting point of mild steel.

The value of $\lambda$ obtained from equation 4.9 a when fitted in the gain curve $G_{II}$, it was not found to give a complete matching between the experimental and estimated value. It was not surprising that the estimated curve fell below the experimental curve at lower temperatures. This is due to the fact that the fall in the hardness value of mild steel with temperature is not as gradual as indicated in equation 4.9 a. Hardness of mild steel falls much faster

at these temperatures. If this is taken into consideration the discrepancy at these temperatures would be considerably reduced. The exact relationship of hardness variation is not available. Hence, this point could not be confirmed directly. However the following approach for the $\lambda$ is found satisfactory.

It is known that temperature at interface is a function of velocity (equation 3.10). So to simplify the equation 4.9 a the variation of $\lambda$ with velocity is intuti assumed to take a form

$$\lambda = 1 - \frac{V_s}{k'}$$

where $k'$ is a constant (a velocity factor)which takes care of the temperature at the interface of sliding.

Since the ratio of hardness at temperatures of melting point of any one body of the sliding pair tends to zero, the interaction factor has not much meaning. So k', for brass rubbing against mild steel, can take that velocity at which the melting of brass occurs(lower melting point when compared to mild steel). Accordingly the value of k' is obtained using equation 3.10 as 85 m/min.

Therefore

$$\lambda = 1 - \frac{1}{85} V_s \qquad (4.9\ b)$$

Since the overall variation of $\lambda$ is similar to variation

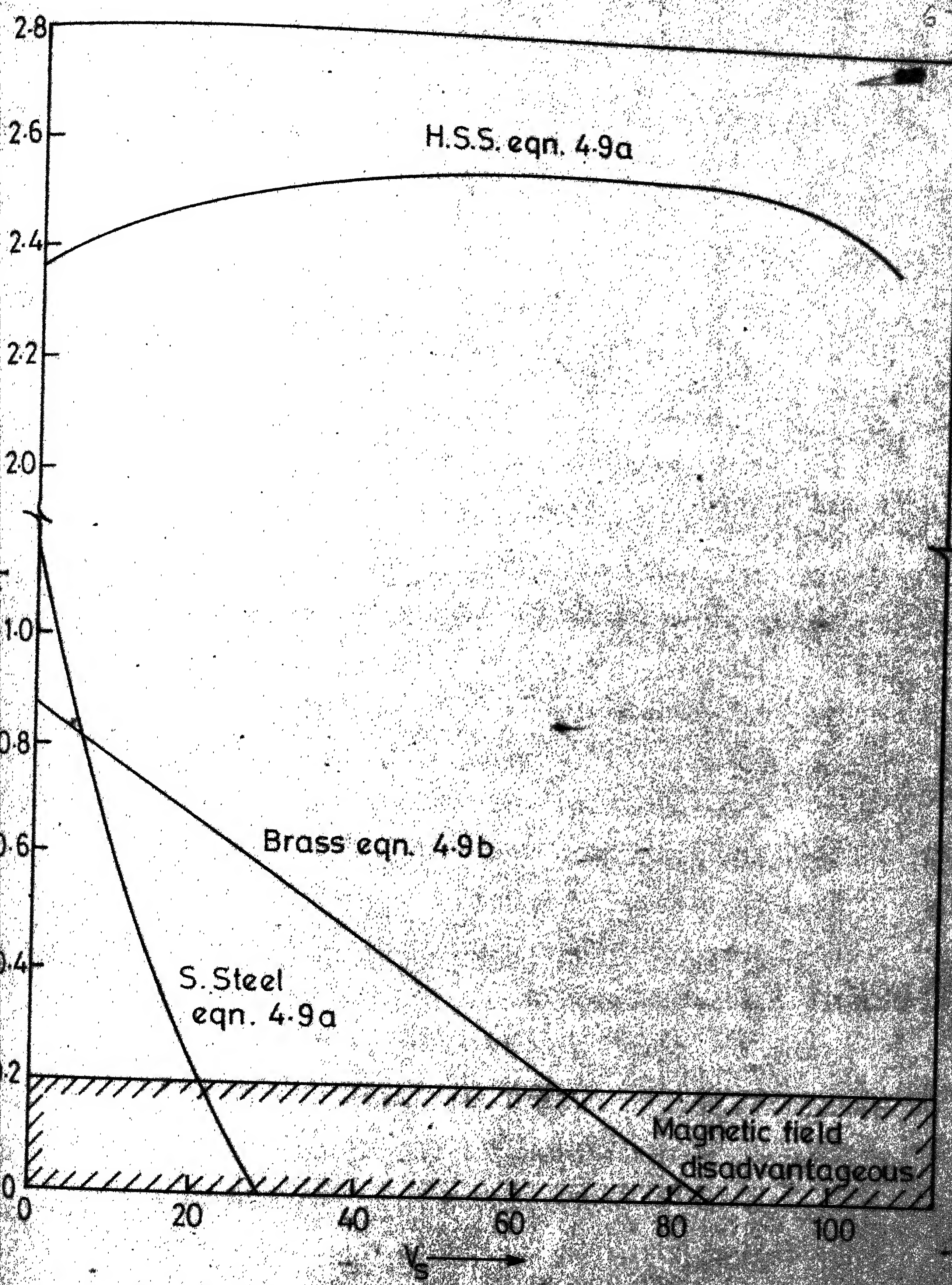



Fig. 13 – Variation of hardness ratio with velocity (temp.)

of hardness ratio with temperature $\lambda$ is still defined as a hardness factor.

Using equation 4.9, $\lambda$ is calculated for the following combination of materials:

1. Mild steel (body I) vs Brass (body II)
2. Mild steel (body I) vs Stainless steel (body II)
3. Mild steel (body I) vs High speed steel (body II)

The variation of the hardness ratio for various rubbing velocities for these cases is plotted in figure 13. As can be seen from this figure and figure 11 for the case of gain factor of brass $G_{II}$ it is observed that the ratio of hardness at critical velocity $V_c^*$ is approximately 0.2. It means that as long as the value of $\lambda$ is more than about 0.2 the gain factor of body II (lower permeability) would be positive. But when the value of $\lambda$ falls below the level $\lambda = 0.2$ the gain factor takes negative values. From this case it appears that the variation of gain factor for body II is strongly dependent upon its hardness relative to the body I and is not perhaps governed by any other factor more strongly.

If it is really so, then the following conditions should hold.

1. Bodies with lower magnetic permeability compared to mild steel and considerably softer than mild steel at

room temperature should hardly yield any positive gain factor. It may in fact yield negative gain factor.

2. Bodies with lower magnetic permeability compared to mild steel and harder than mild steel should yield positive gain factor.

The hardness ratios for mild steel vs stainless steel and mild steel vs high speed steel are plotted in figure 13 along with that of brass vs mild steel. In this figure it is seen that the hardness ratio is above 0.2 only at lower velocities for the case of stainless steel. The value is below 0.2 for most of the velocities in our range. This implies that the gain factor for stainless steel body rubbing against mild steel body will be negative almost throughout the velocity range and can be positive only in the beginning or at lower velocities. To test this hypothesis stainless steel pins were rubbed against mild steel cylinder. The details of the experiment and results are discussed in section 4.5.

Again on the basis of this gain factor of high speed steel rubbing against mild steel should be positive always. This is indeed the case which Ghosh and Bagchi [4,5] have investigated, the work which has formed the foundation for the subsequent work in this area. It seems to be clear now, therefore, the effect of magnetic

field is not only through its influence on one body, but is a two body phenomena. Values of $\lambda$ (Table 4.5) with rubbing velocity can be used to estimate $G_{II}$ if variation of $\bar{\beta}$ is also available.

4.4.2 b Variation of $\bar{\beta}$ with rubbing velocity

As shown in Appendix 2, $\bar{\beta}$ is defined as

$$\bar{\beta} = \frac{m^H_{II}}{m^O_{II}} = \left( \frac{D^H_s}{D^O_s} \right)^{1/6} \tag{4.10}$$

It was already deduced in section 3.3.1 that the ratio of diffusivities in the presence and absence of magnetic field is given by

$$\frac{D^H_s}{D^O_s} = \exp . \frac{\Delta u}{R\,\theta} \tag{3.12}$$

Putting this in equation (4.10), $\bar{\beta}$ can be written as

$$\bar{\beta} = \exp . \frac{\Delta u}{6R\,\theta} \tag{4.11}$$

The value of $\Delta u$ was obtained in section 3.3.1 and putting this value in the equation, the ratio of diffusivities can be evaluated. The variation of this ratio with $\theta$ is shown in figure 14. The results are tabulated in Table 4.5.

Muju and Ghosh [6, 8] had assumed $\frac{D^H_s}{D^c_s}$ to be equal to $\frac{\rho^H}{\rho^O}$. In their model they have also assumed that the dislocation densities $\rho^H$ and $\rho^O$ at notch are a square

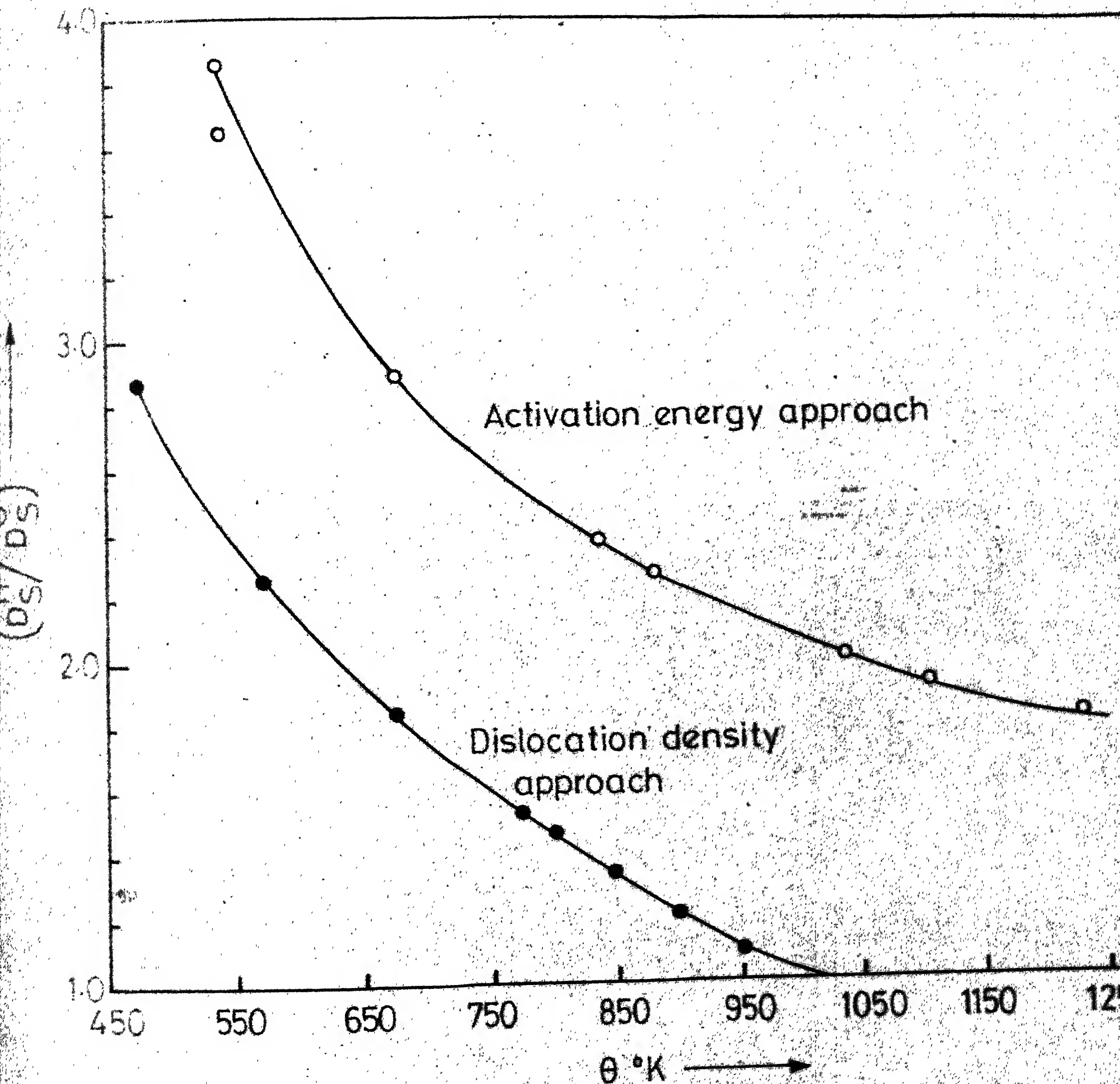



Fig. 14 -Effect of magnetic field on diffusion enhancem

function of $V^H$ and $V^o$, respectively. Hence from their results $\frac{D_s^H}{D_s^o}$ can be obtained as

$$\frac{D_s^H}{D_s^o} = \left( \frac{V^H}{V^o} \right)^2 \tag{4.12}$$

Using equations 2.7 - 2.9 for the velocity of dislocations the above equation can be reduced to

$$\frac{D_s^H}{D_s^o} = \exp. \frac{2 V^* G^* \lambda_s}{k \theta} \tag{4.13}$$

$\lambda_s$ is not a constant but varies with temperature. The variation of $\lambda_s$ with temperature is taken to be similar to the variation of magnetisation with temperature in the following manner

$$\frac{I}{I_o} = 1 - \left( \frac{\theta}{\theta_c} \right)^4 \tag{4.14}$$

where $\theta_c$ = curie point in $^o$k

I and $I_o$ = the intensities of magnetic field at the temperature $\theta$ and absolute zero temperature respectively. Hence the variation

of $\lambda_s$ can be written as

$$\frac{\lambda_s}{\lambda_o} = 1 - \left( \frac{\theta}{\theta_c} \right)^4 \tag{4.15}$$

where $\lambda_s$ = magnetostrictive coefficient at any temperature $\theta$ $^o$k

$\lambda_o$ = magnetostrictive coefficient at room temperature.

Introducing this variation for $\lambda_s$ in equation 4.13 the ratio $\frac{D_s^H}{D_s^O}$ reduces to

$$\frac{D_s^H}{D_s^O} = \exp. \left[ \frac{2\, V^*\, G^*}{k\, \theta}\, \lambda_o \left\{ 1 - \left( \frac{\theta}{\theta_c} \right)^4 \right\} \right] \qquad (4.16)$$

The variation of this ratio obtained with temperature (sliding velocity) is shown in figure 14. It is to be noted that the order of magnitude of enhancement in diffusivity as calculated from equation 4.16 and equation 3.12, is close to each other. This result is of great significance keeping in mind that equations 4.16 and 3.12 are obtained through independent approaches. Equation 4.16 is purely a theoretical equation based on hypothesis that the diffusivity at the asperity junction is enhanced because of enhanced dislocation intersection which would lead to generation of excess vacancies. Equation 3.12 on the other hand is obtained purely on the basis of experimental results obtained during a rubbing test. This agreement in values leads to the possibility that the diffusivity at the asperity junction might indeed be getting enhanced due to enhanced dislocation activity as postulated by previous workers [6, 8].

TABLE 4.5

Estimated and Experimental Values of Gain Factor $G_{II}$

| Rubbing velocity $V_s$ (m/min) | Mass ratio of wear particles $\bar{\beta}$ (eqn.4.11) | Interaction factor $\lambda$ (eqn.4.9 b) | Gain factor for body I $G_I$ (Fig. 10) | Estimated gain factor for body II, $G_{II}$ (eqn. 4.4) | Experimental gain factor for body II $G_{II}$ (Fig. 12) |
|---|---|---|---|---|---|
| 10.0 | 1.2518 | 0.880 | -0.37 | 0.156 | 0.150 |
| 20.0 | 1.1951 | 0.753 | -0.49 | 0.246 | 0.230 |
| 35.0 | 1.5556 | 0.583 | -0.605 | 0.246 | 0.250 |
| 40.0 | 1.1470 | 0.510 | -0.625 | 0.219 | 0.20 |
| 60.0 | 1.1235 | 0.280 | -0.665 | 0.0860 | 0.075 |
| 70.0 | 1.1153 | 0.120 | -0.650 | 0.028 | 0.050 |
| 90.0 | 1.1030 | -0.080 | -0.590 | -0.097 | -0.150 |
| 104.0 | 1.0965 | -0.20 | -0.510 | -0.154 | -0.180 |

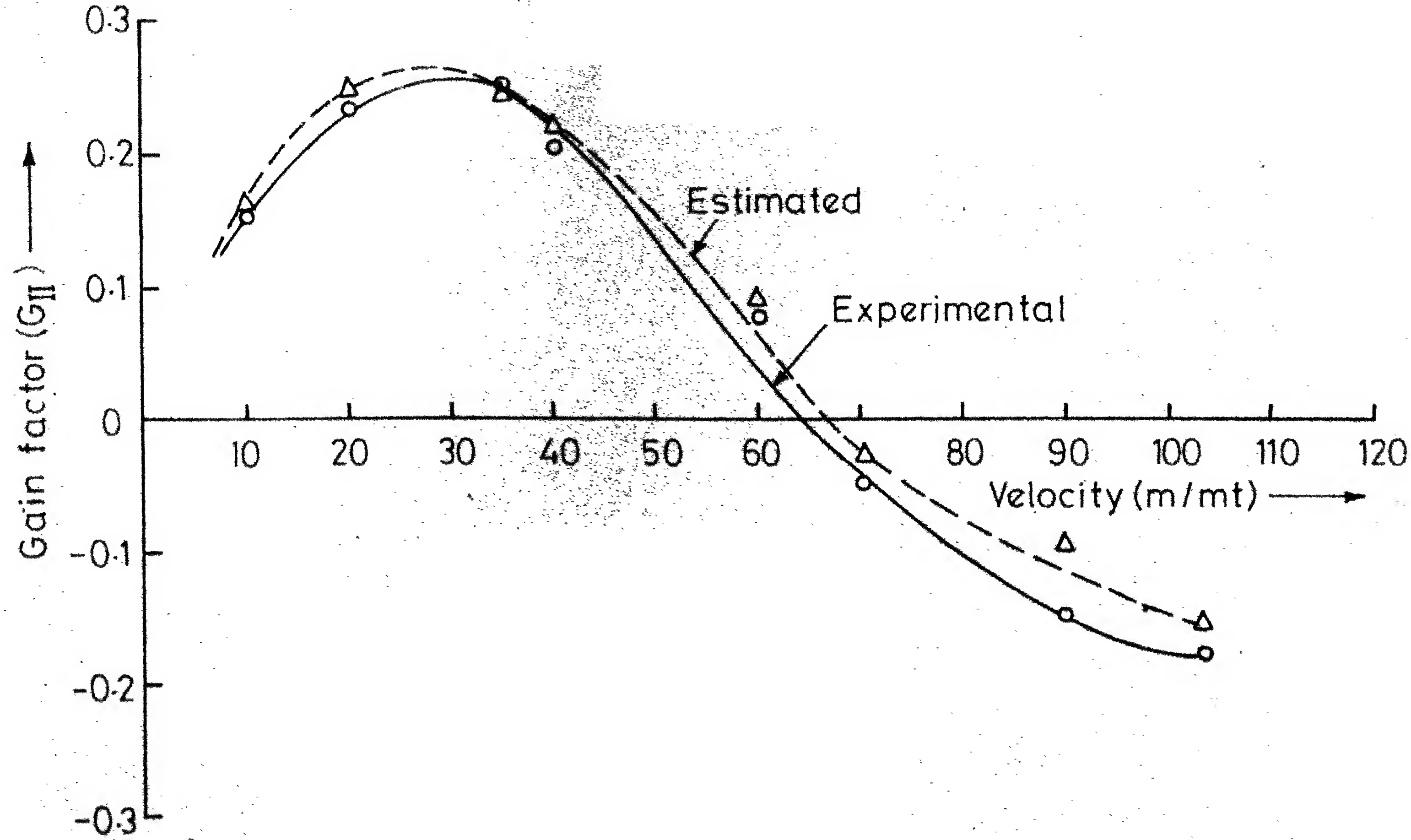



Fig. 15 -Variation of gain factor with rubbing velocity (experimental and estimated).

In the present work the values of $\frac{D^H_s}{D^O_s}$ are obtained purely from wear experiments (Eq. 3.12) discussed in section 3.3.1. The values of $\bar{\beta}$ are given in Table 4.5.

Thus the variation of $G_I$, $\lambda$ and $\bar{\beta}$ with velocity are obtained and now the estimation of $G_{II}$ is carried out. The values of $G_{II}$ are calculated and tabulated in Table 4.5 . This variation in $G_{II}$ plotted in figure 15 against velocity of sliding and it can be seen from the figure that the estimated values for $G_{II}$ are in good agreement with the experimental results. Thus it seems that the various hypothesis as well as experimental conclusions used in the evaluation of $G_{II}$ are fairly true.

## 4.5 Rubbing of Stainless Steel Pins Against Mild Steel Cylinder in the Presence and Absence of Magnetic Field

These results were undertaken mainly to confirm the hypothesis put forward in section 4.4.2(a) that the gain factor, $G_{II}$ for stainless steel is negative at almost all the velocities with in the range of experimentation.

The experimental set-up is the same as that discussed in section 4.4.1 except to that the method of rubbing of the stainless steel pins is similar to that of mild steel pins. Here the wear was measured using a microbalance. The method of experimentation is same as

TABLE 4.6

RUBBING OF STAINLESS STEEL PINS

ON A MILD STEEL CYLINDERS

Feed = 0.075 mm/revol.

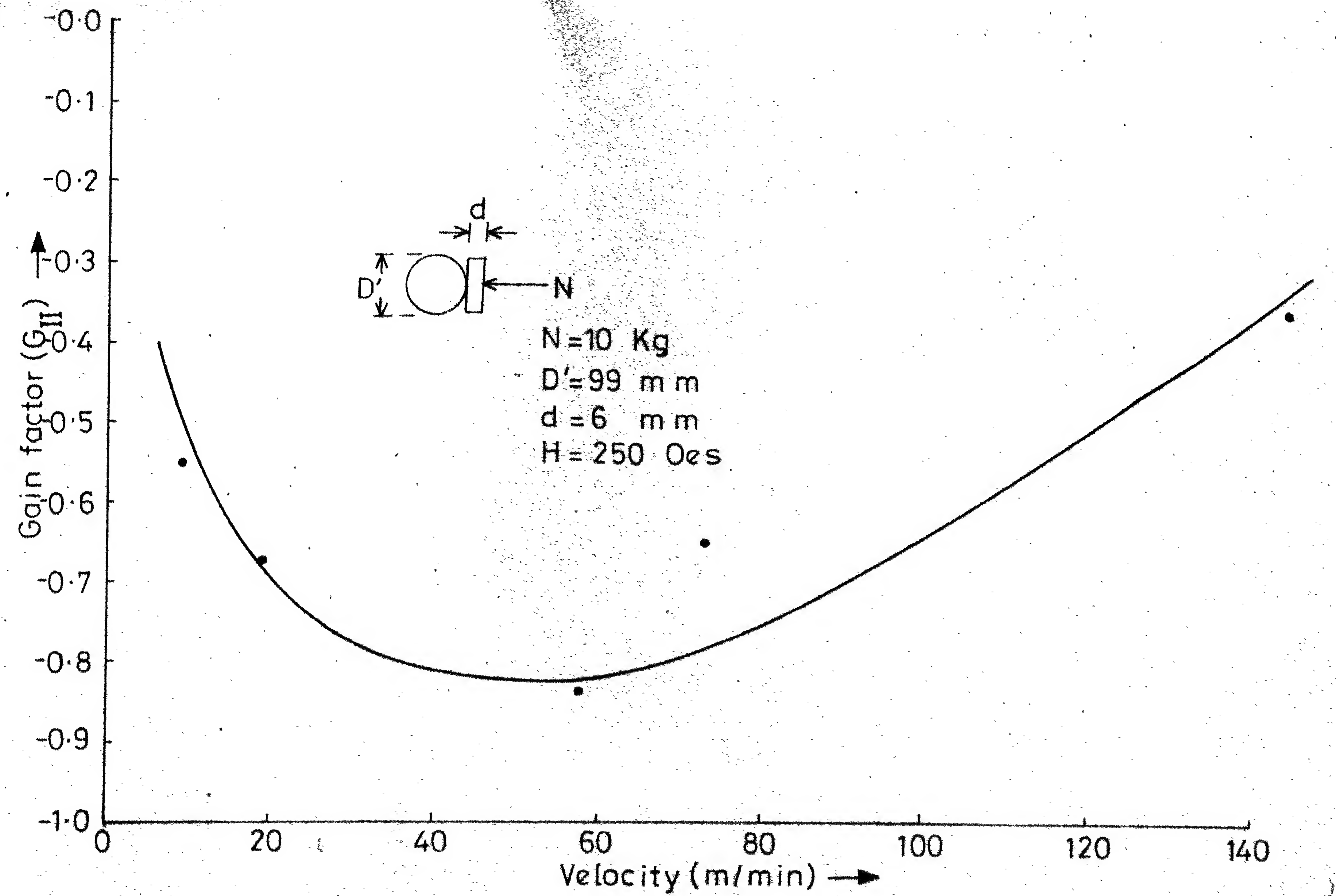
Dia. of S.S. Pin = 6 mm

Dia. of M.S. Cylinder = 99 mm

Load = 10 kg

Magnetic field strength (H) = 250 Oe

| S.No. | Rubbing velocity $V_s$ (m/min) | Rubbing time (min.) | Average wear when H = 0 $W_o$ (gms) | Average wear when H = 0 $W_H$ (gms) | Gain factor $G_{II}$ |
|---|---|---|---|---|---|
| 1 | 9.25 | 2.00 | 0.017947 | 0.028290 | -0.5763 |
| 2 | 18.60 | 1.50 | 0.004524 | 0.007691 | -0.6779 |
| 3 | 58.00 | 0.50 | 0.017411 | 0.032070 | -0.8419 |
| 4 | 73.00 | 0.40 | 0.027932 | 0.045750 | -0.6329 |
| 5 | 146.00 | 0.17 | 0.034611 | 0.046955 | -0.3566 |



Gain factor ($G_{II}$)
Velocity (m/min)
-0·0
-0·1
-0·2
-0·3
-0·4
-0·5
-0·6
-0·7
-0·8
-0·9
-1·0
0
20
40
60
80
100
120
140
d
D'
N
N = 10 Kg
D' = 99 mm
d = 6 mm
H = 250 Oes

that discussed in section 4.2. These experiments were carried out for the feed 0.075 mm/revolution. The results are tabulated in Table 4.6 and plotted in figure 16.

It can be seen that the theoretical reasoning put forward in section 4.4.2(a) is in good agreement with the experimental results. It is to be noted that the gain factor $G_{II}$ at even low velocities is negative. This disagreement with the predicted variation is mainly due to the variation of hardness for the stainless steel. The variati is not exactly as that assumed in evaluation of the ratio of hardness. (Eq. 4.9 a)

### 4.6 Rubbing of Brass Pins Against Mild Steel Cylinder in Presence of Coolant

In the present work it has been assumed that in the wearing of various materials considered, the adhesive wear is predominant mechanism of wear under the conditions used. To verify whether magnetic field was affecting through its influence on adhesive wear it was thought useful to conduct a rubbing test under conditions which would largely reduce the possibility of adhesive wear. This is easily done by doing a rubbing test in presence of a coolant. Accordingly the experiments were conducted on rubbing of brass on mild steel for feed 0.15 mm/revolution in presence of coolant and also in the presence and absence of magnetic field. Cold water was used for this

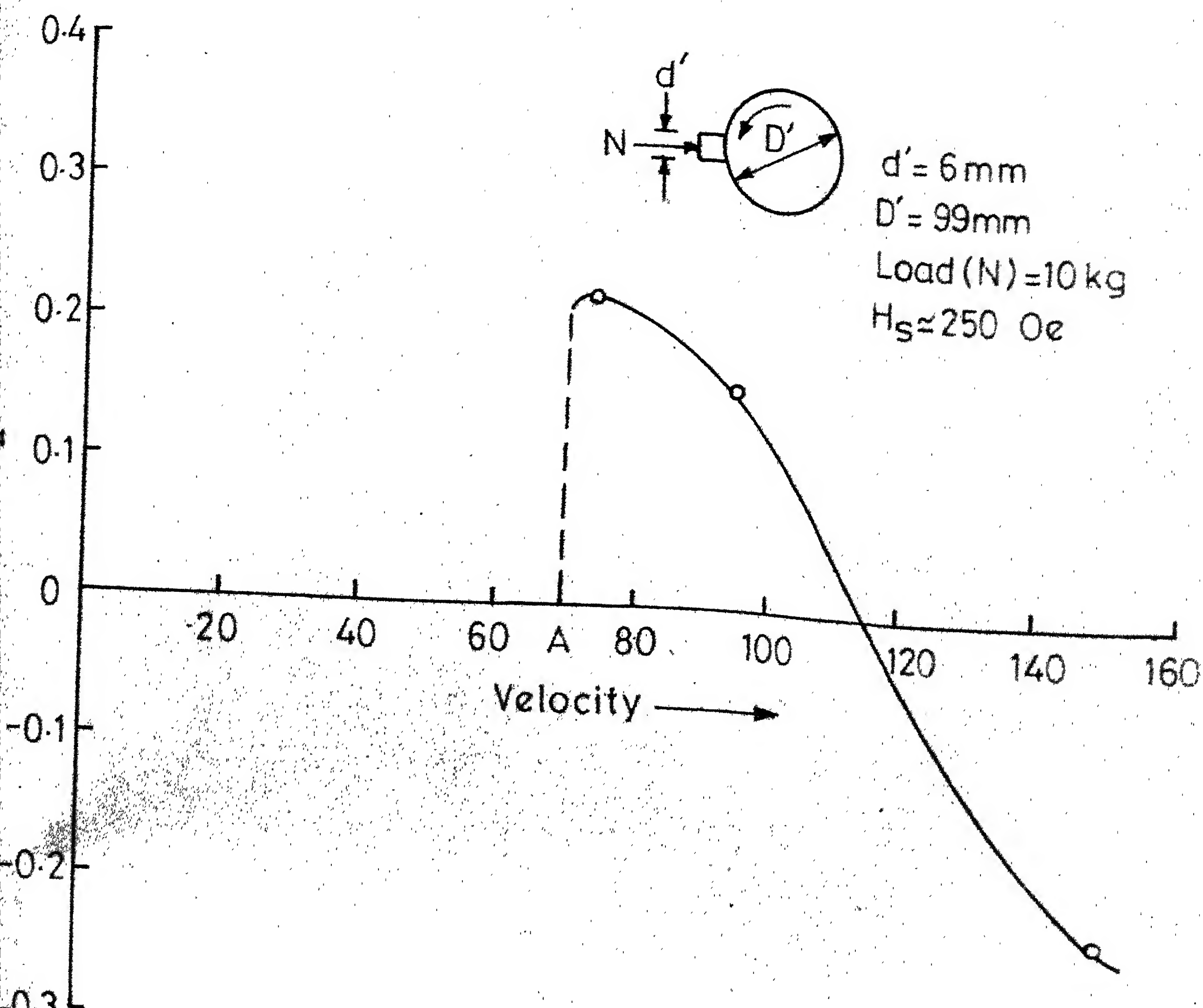



Fig. 17 – Variation of gain factor with velocity in presence of coolant.

purpose. The trend of the results obtained is shown in figure 17.

As seen in the figure the gain factor could not be estimated upto a velocity denoted by point A. However, beyond that velocity the gain factor is positive and has **falling** magnitude. The value of critical velocity is also seen to be shifted to a higher velocity.

Actually in this experiment there was very little wear of brass pin at lower velocities, both in presence and absence of field for the distance rubbed ($\simeq$100 m). The difference in the wear magnitude could not be consistently evaluated and therefore the gain factor remained undefined. Possibly the wear has been purely of abrasion type resulting in very little wear. In the presence of cutting fluids the adhesion wear is expected to be considerably reduced. This might as well lead us to a negligible gain factor at low speeds. It is also known that beyond about 80 metres per minute cutting fluids have a very little lubricating effect [40] . Accordingly beyond same speed the wear behaviour in presence and absence of lubricant would be somewhat similar. The curve in figure 17 depicts that the shift in the critical velocity to a higher magnitude is to be understood primarily due to the cooling effect of the coolant. Due to the limited experiments done in this case no further inferences can be drawn and further work in this direction is strongly suggested.

## 4.7 Elemental Analysis Using Proton Induced X-ray Emission Spectroscopy

In section 3.3.2 the role of diffusivity on negative hardness gradient was discussed. According to that section, at high speeds beyond critical rubbing velocity, brass particles removed should contain considerably more iron in the case of magnetised than in the unmagnetised case. At these speeds the wear particle size removed was found to be considerably larger than at lower speeds. It was possible to take these individual particles and analyse them accurately for their iron, brass ratio. It was decided to use proton induced X-ray emission analysis for the purpose. Inaccuracies involved in the chemical analysis method and the small magnitudes of material available were the primary reasons for selecting this method of analysis. Accordingly as a sample case the wear particles obtained at higher speed 155 m/min and 0.075 mm/revolution feed were taken for the analysis. The obtained emission spectrum is shown in figure 18.

For these tests the particles were put in the form of a pellet. The wear particles were mixed with a fixed amount of potassium bromide (0.085 gms.), which acted as a binder, to form a sound pellet which could be handled in the specimen holder of PIXEA without any difficulty. Potassium bromide was selected for two reasons:

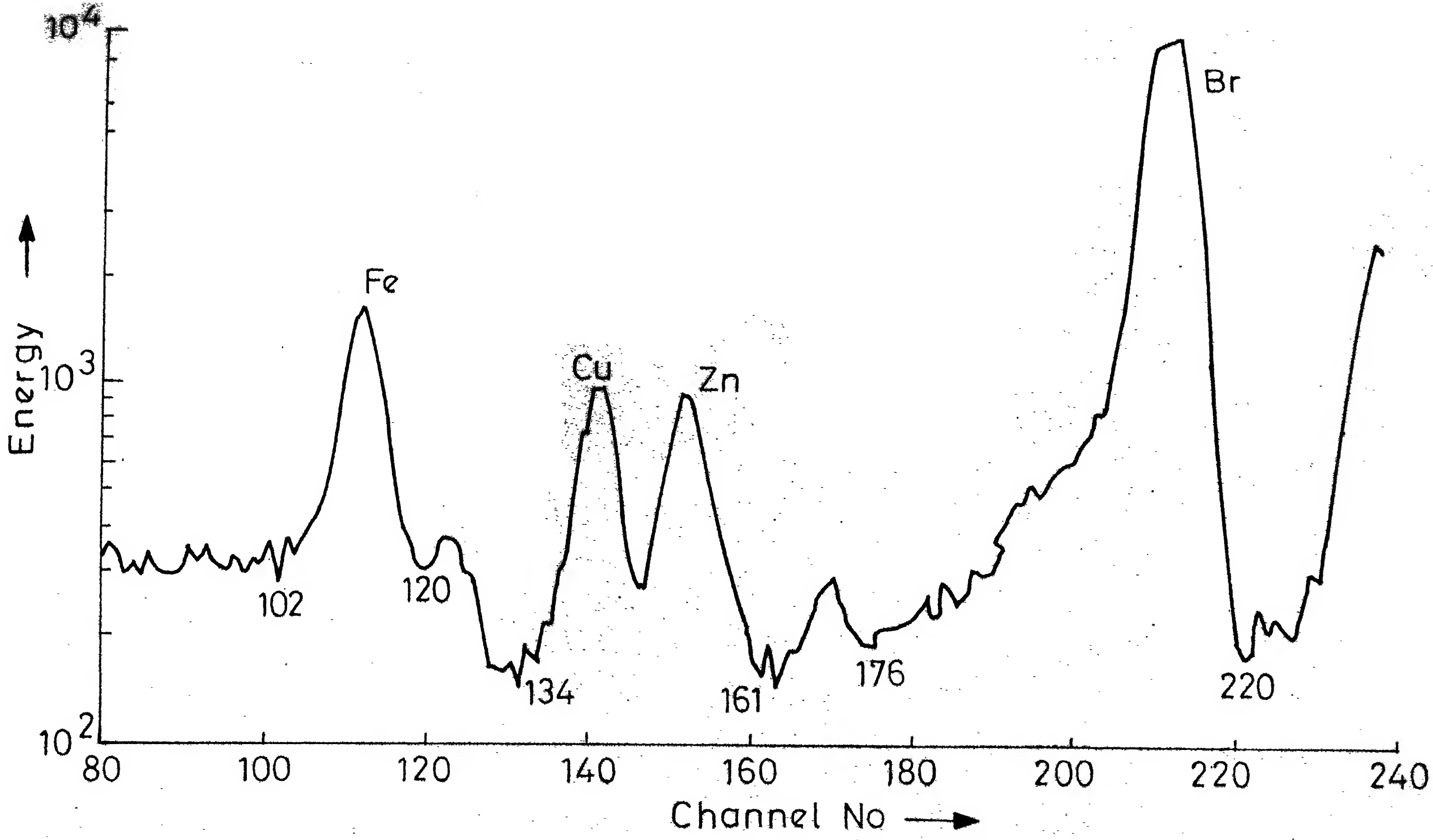



Fig 18. a Spectrum showing energy and channel for the non magnetised wear particle

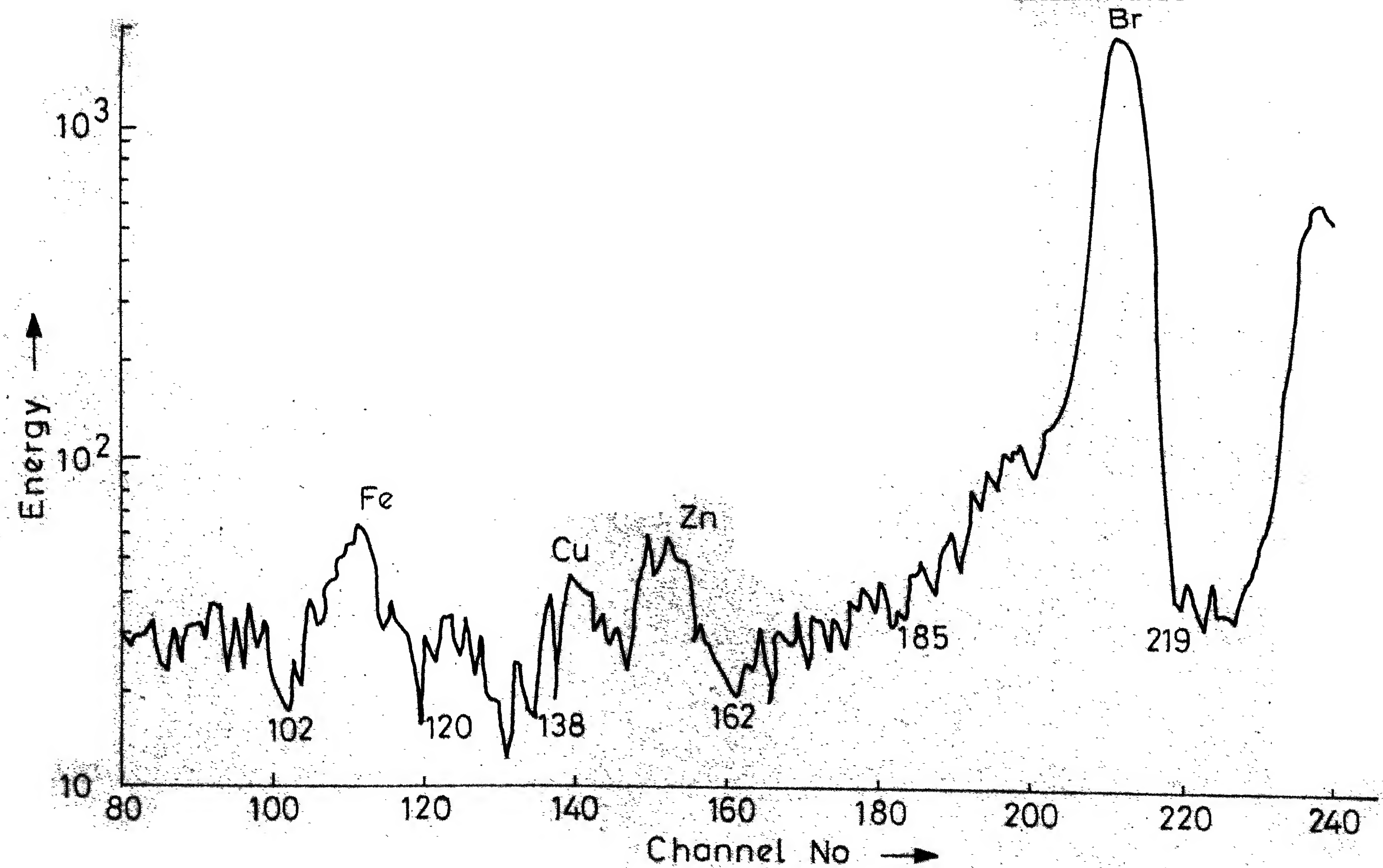



Fig. 18. b Spectrum showing energy and channel for the magnetised wear particle

1. Its emission spectrum does not interfere with those of iron, zinc and copper.
2. It was readily available in pure form.

The spectrum is analysed and the results are give in Table 4.7. As can be seen from the table, iron, brass ratio is greater in the case of magnetic field case than in the absence of magnetic field. This is interestingly in agreement with the expectation and postulates that at higher velocities of rubbing the negative hardness gradient leads to increase in wear of brass.

TABLE 4.7

| Sample | Iron per unit of bromine | Brass per unit of bromine | Iron to brass ratio |
|---|---|---|---|
| Unmagnetised case | 0.10676 | 0.12410 | 0.8603 |
| Magnetised case | 0.03091 | 0.02336 | 1.3232 |

## CHAPTER V

## CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

1. Application of magnetic field reduces the activation energy for wear.

2. The activation energy for wear is of the same order of magnitude as the activation energy of diffusion at high strain rates. A dynamic diffusion test in presence and absence of magnetic field is suggested.

3. The absolute value of gain factor is dependent upon the extent to which the wear is occuring along a fresh trac and the repeated track.

4. The enhancement in the diffusivity in strained condition due to the application of magnetic field seems to be well related with the enhancement in the dislocation density at an asperity junction.

5. Application of a magnetic field to a rubbing pair would be advantageous only if the following condition is satisfied.

$$\frac{\text{Hardness of body of lower magnitude permeability}}{\text{Hardness of body of higher magnetic permeability}} > 0.2$$

This suggests that the machinability of mild steel by tungstan carbide in presence of magnetic field would be improved and therefore future work in this direction is suggested.

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# APPENDIX 1

If, in the case of diffusion of iron (mild steel) into brass, the hardness of the surface layer of II at depth x is assumed to follow the same profile as the concentration gradient, the following equation results.

$$H_{II}\ (x,\ t) \ = \ H\ (1 + \beta_1\ C) \qquad (A\text{-}1)$$

where, $H_{II}\ (x, t)$ = hardness of body II at any x and t,

$H$ = hardness of body II in the bulk,

$\beta_1$ = constant of proportionality,

and $C$ = concentration of the diffusing element in II

$$= C_o\ \mathrm{erfc}\ \left( \frac{x}{\sqrt{4\ D\ t_o}} \right) \qquad (A\text{-}2)$$

Here $D$ = diffusion coefficient

$C_o$ = concentration of the diffusing material at the interface.

In this analysis it is assumed that the fracture in body II would occur along a path which offers the least resistance. Since the negative hardness gradient creates a weak path beneath the surface a resistance parameter $\Omega$ should be minimum along the path, where $\Omega$ has been defined as

$$\Omega \ = \ \int H_{II}\ (x)\ ds \qquad (A\text{-}3)$$

where $ds$ = A small element along the assumed path.

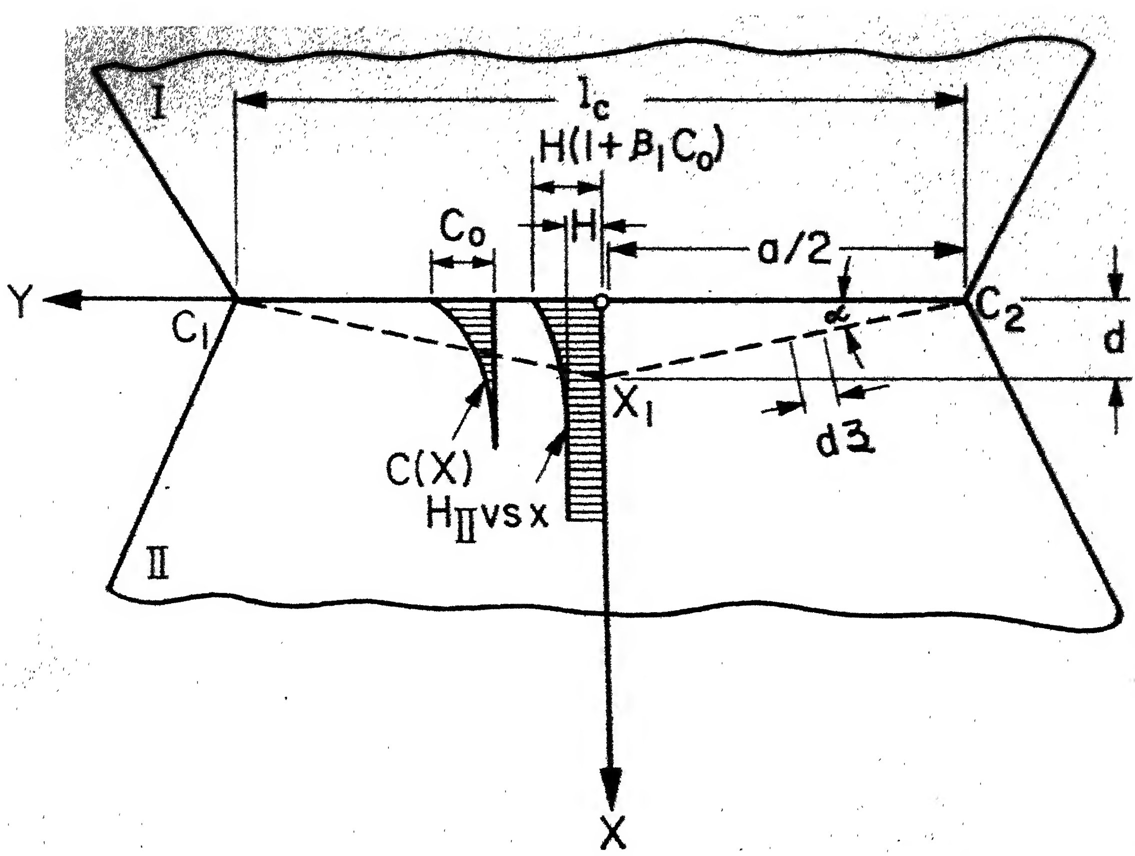


Fig. I Figure Showing Influence Of Diffusion On Hardness. Diffusion Of Element Of I Into II Is Considered. Diffusion Is Considered To Be Only In X Direction

For the case of a triangular path $C_1 X_1 C_2$, fig I, the maximum depth d of the fracture path obtained by minimization of $\Omega$ , is given by

$$d^3 = \frac{a^2}{8} \sqrt{\frac{4 D t_o}{\pi}} \qquad \text{(A-4)}$$

where a = asperity junction width,

$t_o$ = junction time.

It can be seen from this equation that

$$d \propto D^{1/6} \qquad \text{(A-5)}$$

Thus if diffusivity of the element diffusing from I into II increases from $D_s^O$ to $D_s^H$, the depth $d_2$ of the fracture path is expected to be deeper and given by

$$d_2 = d_1 \left( \frac{D_s^H}{D_s^O} \right)^{1/6} \qquad \text{(A-6)}$$

## APPENDIX 2

In Appendix 1 it has been shown how the depth of the fracture zone $d$ , changes with a change in diffusivity. Since the volume of the material removed as a wear particle is proportional to d, the ratio of the mass of the wear particle of body II in the presence and absence of the magnetic field is written as

$$\frac{m_{II}^{H}}{m_{II}^{o}} = \left( \frac{D_s^H}{D_s^o} \right)^{1/6} = \bar{\beta} \qquad (B.1)$$

where $m_{II}^{H}$ and $m_{II}^{o}$ = mass of the wear particle of body II in the presence and absence of the magnetic field, respectively.

It can be seen from equation B.1 that the value of $\bar{\beta}$ is always greater than unity. The gain factor for body II can from definition be written as

$$G_{II} = \frac{m_{II}^{o}\ n_{II}^{o} - m_{II}^{H}\ n_{II}^{H}}{m_{II}^{o}\ n_{II}^{o}}$$

$$= 1 - \bar{\beta}\ \frac{n_{II}^{H}}{n_{II}^{o}} \qquad (B.2)$$

where $n_{II}^{H}$ and $n_{II}^{o}$ = number of fractures during a given time occuring on the side of body I, when magnetic field is applied and when no magnetic field is applied respectively.

The gain factor for body I can be written as

$$G_I = \frac{n_I^o - n_I^H}{n_I^o}$$

$$= \left( \frac{\bar{n}_{II}^H}{n_{II}^o} - 1 \right) \frac{n_{II}^o}{n_I^o} \qquad (B.3)$$

$G_I$ is negative for the mild steel (body I) all along the velocity range used in this work.

Using equation B.2 and B.3 it is easily seen that

$$G_{II} = 1 - \bar{\beta} \left( \frac{G_I \, n_I^o}{n_{II}^o} + 1 \right)$$

$$= 1 - \bar{\beta} \, (1 + G_I \, \lambda) \qquad (B.4)$$

It is clear therefore, that the sign as well as magnitude of $G_{II}$ depends upon the magnitude of the quantity $\bar{\beta}\,(1 + G_1\,\lambda)$. Since both $G_I$ and $\lambda$ are less than unity and $\bar{\beta}$ is greater than unity, the quantity $\bar{\beta}\,(1 + G_I\,\lambda)$ is always positive. Therefore $G_{II}$ will be positive, zero or negative depending upon whether

$$\bar{\beta}\,(1 + G_1\,\lambda) < 1$$
$$= 1$$
$$> 1$$

Therefore the nature of variation of $G_{II}$ will be controlled by the nature of variation of $G_I$.